

This is a repository copy of *Effects of N-Glycosylation Site Removal in Archaellins on the Assembly and Function of Archaella in Methanococcus maripaludis*.

White Rose Research Online URL for this paper:

<https://eprints.whiterose.ac.uk/83841/>

Version: Published Version

Article:

Ding, Yan, Uchida, Kaoru, Aizawa, Shin-Ichi et al. (5 more authors) (2015) Effects of N-Glycosylation Site Removal in Archaellins on the Assembly and Function of Archaella in Methanococcus maripaludis. PLoS ONE. e0116402. ISSN 1932-6203

<https://doi.org/10.1371/journal.pone.0116402>

Reuse

Items deposited in White Rose Research Online are protected by copyright, with all rights reserved unless indicated otherwise. They may be downloaded and/or printed for private study, or other acts as permitted by national copyright laws. The publisher or other rights holders may allow further reproduction and re-use of the full text version. This is indicated by the licence information on the White Rose Research Online record for the item.

Takedown

If you consider content in White Rose Research Online to be in breach of UK law, please notify us by emailing eprints@whiterose.ac.uk including the URL of the record and the reason for the withdrawal request.

RESEARCH ARTICLE

Effects of *N*-Glycosylation Site Removal in Archaeallins on the Assembly and Function of Archaeella in *Methanococcus maripaludis*

Yan Ding¹, Kaoru Uchida², Shin-Ichi Aizawa², Kathleen Murphy³, Alison Berezuk³, Cezar M. Khursigara³, James P. J. Chong⁴, Ken F. Jarrell^{1*}

1 Department of Biomedical and Molecular Sciences, Queen's University, Kingston, Ontario, Canada, **2** Department of Life Sciences, Prefectural University of Hiroshima, 562 Nanatsuka, Shobara, Hiroshima, Japan, **3** Department of Molecular and Cellular Biology, University of Guelph, Guelph, Ontario, Canada, **4** Department of Biology, University of York, Heslington, York, United Kingdom

* jarrellk@queensu.ca



OPEN ACCESS

Citation: Ding Y, Uchida K, Aizawa S-I, Murphy K, Berezuk A, Khursigara CM, et al. (2015) Effects of *N*-Glycosylation Site Removal in Archaeallins on the Assembly and Function of Archaeella in *Methanococcus maripaludis*. PLoS ONE 10(2): e0116402. doi:10.1371/journal.pone.0116402

Academic Editor: Frederique Lisacek, Swiss Institute of Bioinformatics, SWITZERLAND

Received: October 8, 2014

Accepted: December 9, 2014

Published: February 20, 2015

Copyright: © 2015 Ding et al. This is an open access article distributed under the terms of the [Creative Commons Attribution License](https://creativecommons.org/licenses/by/4.0/), which permits unrestricted use, distribution, and reproduction in any medium, provided the original author and source are credited.

Data Availability Statement: All relevant data are within the paper.

Funding: This work is supported by grants from the Natural Sciences and Engineering Research Council of Canada (NSERC) to K.F.J. and C.M.K. and Biotechnology and Biological Sciences Research Council (BBSRC) to J.P.J.C. K.F.J. was the recipient of a Leverhulme Trust Visiting Professorship. Y.D. thanks the China Scholarship Council (20100622028) for financial support. The funders had no role in study design, data collection and analysis, decision to publish, or preparation of the manuscript.

Abstract

In *Methanococcus maripaludis* S2, the swimming organelle, the archaeellum, is composed of three archaeallins, FlaB1_{S2}, FlaB2_{S2} and FlaB3_{S2}. All three are modified with an *N*-linked tetrasaccharide at multiple sites. Disruption of the *N*-linked glycosylation pathway is known to cause defects in archaeella assembly or function. Here, we explored the potential requirement of *N*-glycosylation of archaeallins on archaeellation by investigating the effects of eliminating the 4 *N*-glycosylation sites in the wildtype FlaB2_{S2} protein in all possible combinations either by Asn to Glu (N to Q) substitution or Asn to Asp (N to D) substitutions of the *N*-glycosylation sequon asparagine. The ability of these mutant derivatives to complement a non-archaellated $\Delta flaB2_{S2}$ strain was examined by electron microscopy (for archaeella assembly) and swarm plates (for analysis of swimming). Western blot results showed that all mutated FlaB2_{S2} proteins were expressed and of smaller apparent molecular mass compared to wildtype FlaB2_{S2}, consistent with the loss of glycosylation sites. In the 8 single-site mutant complements, archaeella were observed on the surface of Q2, D2 and D4 (numbers after N or Q refer to the 1st to 4th glycosylation site). Of the 6 double-site mutation complementations all were archaeellated except D1,3. Of the 4 triple-site mutation complements, only D2,3,4 was archaeellated. Elimination of all 4 *N*-glycosylation sites resulted in non-archaellated cells, indicating some minimum amount of archaeillin glycosylation was necessary for their incorporation into stable archaeella. All complementations that led to a return of archaeella also resulted in motile cells with the exception of the D4 version. In addition, a series of FlaB2_{S2} scanning deletions each missing 10 amino acids was also generated and tested for their ability to complement the $\Delta flaB2_{S2}$ strain. While most variants were expressed, none of them restored archaeellation, although FlaB2_{S2} harbouring a smaller 3-amino acid deletion was able to partially restore archaeellation.

Competing Interests: The authors have declared that no competing interests exist.

Introduction

N-glycosylation is a prevalent protein modification found in all three domains of life in which the attachment of the glycan is via the nitrogen atom in asparagine residues located in the acceptor glycoprotein [1–6]. General features of the N-glycosylation pathways are shared among the three domains [1–3,5,7,8]. The N-glycan precursor is first synthesized on a phosphorylated isoprene-based lipid carrier, either a dolichol derivative in Eukarya and Archaea, or an undecaprenol derivative in Bacteria, via the activities of glycosyltransferases. The assembled lipid-linked glycan is then flipped across a membrane, i.e. to face into the lumen of the endoplasmic reticulum in Eukarya or to the external face of the cytoplasmic membrane in Archaea and Bacteria. A signature enzyme of the pathway, the oligosaccharyltransferase (OST), transfers the completed glycan *en bloc* from its lipid carrier to select Asn residues in target proteins, although further sugars can still be added to the protein-bound glycan. The Asn residue to which the N-glycan is attached is usually located in an Asn-Xaa-Ser/Thr sequon (Xaa cannot be Pro), although in some Bacteria, i.e. *Campylobacter* spp., a negatively charged amino acid residue is also needed at the -2 position. Between the two prokaryotic domains, Bacteria and Archaea, N-glycosylation appears to be much more widespread among Archaea, where 166 of 168 sequenced genomes examined contained at least one copy of a gene encoding the archaeal OST AglB [9]. A variety of archaeal proteins, mainly S-layer proteins and the subunits of surface structures including both pilins and archaeallins (formerly archaeal flagellins [10]), have been shown to be modified with N-glycans [11–18]. Recent work on archaeal N-glycosylation systems has combined both structural and genetic methods, typically using archaeallins and S-layer proteins as reporter proteins. Since the first archaeal glycosylation (*agl*) genes were identified in 2006 [14,19], this combined approach has focused on a few key archaeal model organisms [20]: *Methanococcus maripaludis* S2, *Methanococcus voltae* PS, *Haloferax volcanii* H53 and *Sulfolobus acidocaldarius* MW001 [1,6,11,12,15,16,21]. Interestingly, the N-glycosylation pathway is not essential for any of the three studied euryarchaeotes (*M. maripaludis* S2, *M. voltae* PS and *Hfx. volcanii* H53), as mutants carrying a deletion or insertional inactivation of *aglB* were readily obtained [14,19,22]. However, in the crenarchaeote *S. acidocaldarius* MW001, repeated attempts to delete or interrupt *aglB* were unsuccessful and only the integration of a second copy of *aglB* into the genome allowed for the deletion of the original *aglB* [23]. The key reported effects that result from perturbation or complete abolition of the N-glycosylation pathway in Archaea are on S-layer stability, growth of cells at high salinities and on archaeellation and motility [18,19,22,24–30].

The archaeellum (formerly archaeal flagellum) is the major motility apparatus found in Archaea [10]. It is a rotating appendage unrelated to the bacterial flagellum but bearing instead similarities to the bacterial type IV pilus. These similarities include homologous ATPase and membrane platform proteins involved in assembly of the structure as well as similarities in their major structural proteins [31–35]. The structural proteins, called archaeallins, are made as preproteins with class III (type IV pilin-like) signal peptides which are removed by a specific prepilin peptidase-like enzyme (termed FlaK in methanogens or PibD in Sulfolobales and halo-philis) [36–39]. Signal peptide removal is critical for incorporation of archaeallins into the filament [37, 39]. In addition, it appears that archaeallins are commonly modified with N-linked glycans and interruption of the normal N-glycosylation pathway leads to defects in archaeella assembly or function [1,40]. In species where *aglB* has been deleted or insertional inactivated (*M. voltae* PS, *M. maripaludis* S2, *Hfx. volcanii* H53), the cells are unable to make archaeella. If the pathway is interrupted at steps that lead to a truncated glycan, there is an impairment in motility, although archaeella are still made unless the truncation is too great [18,19,22]. In *M. maripaludis* S2 strain, archaeella contain 3 archaeallins: the major archaeallins FlaB1_{S2} and FlaB2_{S2} form the filament while the minor archaeallin FlaB3_{S2} comprises the hook region [41].

The three archaeallins share sequence similarities including a class III signal peptide cleaved by FlaK, conserved N-terminal and C-terminal regions, and a hypervariable region in the middle [41]. The hypervariable regions of FlaB1_{S2}, FlaB2_{S2} and FlaB3_{S2} are decorated at multiple positions with a unique tetrasaccharide [11]. Cells are archaeallated if they carry deletions in *agl* genes that result in a N-glycan of at least two sugars, but non-archaeallated if the deleted *agl* gene results in a glycan of only a single sugar or prevents N-glycosylation totally (as in an *aglB* deletion) [22,42,43]. These results could mean that the archaeallins must be glycosylated at some or all of its glycosylation sequons by at least a two sugar glycan for those archaeallins to be assembled into a structure. However, an alternative explanation is that the necessity for the glycosylation lies at a different step in archaeella assembly.

A major goal of this study was to examine the requirement of N-glycosylation of the major archaeallin FlaB2_{S2} for archaeallation in *M. maripaludis* S2. FlaB2_{S2} has five N-glycosylation sequons, ²⁶NTS²⁸, ⁶⁶NIT⁶⁸, ¹¹⁰NLT¹¹², ¹¹⁹NTT¹²¹ and ¹²⁴NWS¹²⁶. The first sequon ²⁶NTS²⁸ located in the N-terminal conserved region was previously reported to be unoccupied with glycan while the remaining four, located in the hypervariable region, were modified with tetrasaccharide (Fig. 1, [11]). For these experiments, we eliminated the 4 occupied sequons (⁶⁶NIT⁶⁸, ¹¹⁰NLT¹¹², ¹¹⁹NTT¹²¹ and ¹²⁴NWS¹²⁶, designated as the 1st, 2nd, 3rd and 4th N-glycosylation site, respectively) in all possible combinations (creating single-, double-, triple- and quadruple-site mutations in FlaB2_{S2}). We also generated a series of FlaB2_{S2} scanning deletions in an attempt to determine regions of the molecule that were essential for assembly of archaeella.

Materials and Methods

Strains and growth conditions

M. maripaludis S2 Δ hpt (Mm900) [44], *M. maripaludis* S2 Δ hpt Δ flaB2_{S2} (Δ flaB2_{S2} in short hereafter) [41] and all complemented strains, as well as *M. maripaludis* Δ RC (formerly *Methanococcus deltae* Δ RC [45,46]) were routinely cultured anaerobically in 125 mL sealed serum bottles containing 10 mL Balch medium III under an atmosphere of CO₂:H₂ (20:80) at 37°C with shaking [47]. Cells carrying a complementation plasmid were cultured in the presence of 2.5 μ g/mL puromycin for plasmid selection [48]. For swarming assays, cells were inoculated onto plates of Balch medium III containing 0.25% (w/v) agar in the presence of 2.5 μ g/mL puromycin [22]. *Escherichia coli* TOP 10 cells (Invitrogen Inc.), used for molecular cloning steps, were cultured at 37°C in Luria Broth (LB) medium with shaking or on LB plates (containing 1.5% w/v agar) in the presence of 100 μ g/mL ampicillin for plasmid selection. Strains and plasmids used in this study are listed in Table 1.

Construction of mutant *flaB2_{S2}* genes using site-directed mutagenesis (SDM)

To generate mutant *flaB2_{S2}* genes, the wildtype *flaB2_{S2}* gene was first cloned into the pCR2.1-TOPO-TA vector (Invitrogen Inc.) to create pKJ902. This pCR2.1-TOPO-*flaB2_{S2}* and its derivatives were used as template to generate the mutants listed in Table 2. The wildtype *flaB2_{S2}* gene used in cloning was generated by PCR using the complementation primers listed in Table 3 and genomic DNA from Mm900 as template.

To generate the mutant *flaB2_{S2}* genes that would encode proteins in which N-glycosylation sites were eliminated, the SDM protocol was employed [49]. Forward and reverse mutagenic primer pairs were designed with nucleotide changes located in the middle of the primer that would result in a change of the N-glycosylation sequon Asn residue (Table 3). Purified PCR products were digested with *DpnI* to remove the template plasmid, repurified and then

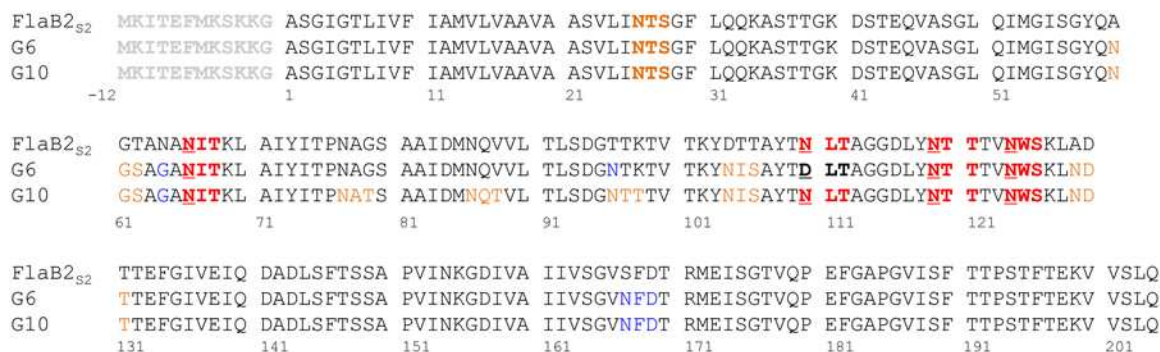


Fig 1. Protein sequence alignment of FlaB2_{s2}, G6 (FlaB2_{ΔRC}) and G10. Signal peptide is shown in grey; the first sequon ²⁶NTS²⁸ that is not occupied with N-glycan is shown in orange; the 4 occupied N-glycosylation sequons are shown in red; the 3-amino acid ⁶¹GTA⁶³ deletion in 3AA is shown in green; extra sequons in the G6 and G10 are also shown in orange; sequences differences from FlaB2_{s2} in G6 and G10 that do not introduce new sequons are shown in blue.

doi:10.1371/journal.pone.0116402.g001

transformed into *E. coli* TOP10 competent cells. Plasmids extracted from the transformants were sequenced to confirm the mutation. Using this method, 8 single-site mutant *flaB2_{s2}* genes were generated that resulted in 4 N to Q single-site mutations and 4 N to D single-site mutations in their protein products. Double-site mutant *flaB2_{s2}* genes were then generated using the plasmids with the single-site changes in *flaB2_{s2}* as template. The same strategy was used to create the triple and quadruple glycosylation site mutant *flaB2_{s2}* genes. The multi-site mutant proteins all contained N to D changes only.

The G6 (*flaB2_{ΔRC}*) gene was amplified by PCR using *M. maripaludis* ΔRC whole cells as template with the complementation primers in Table 3 and subsequently cloned into pCR2.1-TOPO. The G10 gene whose protein product contains additional glycosylation sites was chemically synthesized by GenScript USA Inc. (Piscataway, NJ).

Table 1. Strains and plasmids used in this study.

| Strains | | References |
|---|--|-----------------|
| <i>M. maripaludis</i> | | |
| <i>M. maripaludis</i> S2 Δhpt (Mm900) | | 44 |
| <i>M. maripaludis</i> S2 Δhpt Δ <i>flaB2_{s2}</i> | | 41 |
| <i>M. maripaludis</i> ΔRC | | 46 |
| <i>E. coli</i> | | |
| <i>E. coli</i> TOP10 | | Invitrogen Inc. |
| Plasmids | | |
| pCR2.1-TOPO | TA cloning vector, Amp ^r , Kan ^r | Invitrogen Inc. |
| pKJ902 | <i>flaB2_{s2}</i> in vector pCR2.1-TOPO | This study |
| pCR2.1-TOPO- <i>flaB2_{s2}</i> derivatives | Mutant <i>flaB2_{s2}</i> genes * in vector pCR2.1-TOPO | This study |
| pWLG40 | <i>hmv</i> promoter-lacZ fusion plus Pur ^r cassette; Amp ^r | 48 |
| pKJ1064 | <i>flaB2_{s2}</i> in shuttle vector pWLG40 under a <i>hmv</i> promoter | This study |
| pWLG40- <i>flaB2_{s2}</i> derivatives* | Mutant <i>flaB2_{s2}</i> genes * in vector pWLG40 | This study |

* Please refer to Table 2

doi:10.1371/journal.pone.0116402.t001

Table 2. Mutated FlaB2S2 derivatives generated in this study.

| Mutated FlaB2 derivatives | Description |
|--|--|
| Control | |
| WT | Wildtype <i>flaB2_{S2}</i> from <i>M. maripaludis</i> S2 |
| Mutated FlaB2 derivatives containing mutations at N-glycosylation sites | |
| N to Q single-site mutation | |
| Q1 | FlaB2 _{S2} N66Q |
| Q2 | FlaB2 _{S2} N110Q |
| Q3 | FlaB2 _{S2} N119Q |
| Q4 | FlaB2 _{S2} N124Q |
| N to D single-site mutation | |
| D1 | FlaB2 _{S2} N66D |
| D2 | FlaB2 _{S2} N110D |
| D3 | FlaB2 _{S2} N119D |
| D4 | FlaB2 _{S2} N124D |
| N to D double-site mutation | |
| D1,2 | FlaB2 _{S2} N66D N110D |
| D1,3 | FlaB2 _{S2} N66D N119D |
| D1,4 | FlaB2 _{S2} N66D N124D |
| D2,3 | FlaB2 _{S2} N110D N119D |
| D2,4 | FlaB2 _{S2} N110D N124D |
| D3,4 | FlaB2 _{S2} N119D N124D |
| N to D triple-site mutation | |
| D1,2,3 | FlaB2 _{S2} N66D N110D N119D |
| D1,2,4 | FlaB2 _{S2} N66D N110D N124D |
| D1,3,4 | FlaB2 _{S2} N66D N119D N124D |
| D2,3,4 | FlaB2 _{S2} N110D N119D N124D |
| N to D quadruple-site mutation | |
| D1,2,3,4 | FlaB2 _{S2} N66D N110D N119D N124D |
| Mutated FlaB2_{S2} with extra N-glycosylation sequons | |
| G6 | FlaB2 _{S2} ⁶⁰ AGT ⁶² to ⁶⁰ NGS ⁶² , ¹⁰⁴ DDT ¹⁰⁶ to ¹⁰⁴ NIS ¹⁰⁶ , N110D, A129N |
| G10 | FlaB2 _{S2} ⁶⁰ AGT ⁶² to ⁶⁰ NGS ⁶² , G79T, V88T, ⁹⁶ TTK ⁹⁸ to ⁹⁶ NTT ⁹⁸ , ¹⁰⁴ DDT ¹⁰⁶ to ¹⁰⁴ NIS ¹⁰⁶ , A129N |
| Ten-amino acid scanning deletions | |
| Δ2–10 | FlaB2 _{S2} missing ² SGIGTLIVF ¹⁰ |
| Δ4–10 | FlaB2 _{S2} missing ⁴ IGTLIVF ¹⁰ |
| Δ11–20 | FlaB2 _{S2} missing ¹¹ IAMVLVAAVA ²⁰ |
| Δ21–30 | FlaB2 _{S2} missing ²¹ ASVLINTSGF ³⁰ |
| Δ31–40 | FlaB2 _{S2} missing ³¹ LQQKASTTGK ⁴⁰ |
| Δ41–50 | FlaB2 _{S2} missing ⁴¹ DSTEQVASGL ⁵⁰ |
| Δ51–60 | FlaB2 _{S2} missing ⁵¹ QIMGISGYQA ⁶⁰ |
| Δ61–70 | FlaB2 _{S2} missing ⁶¹ GTANANITKL ^{70 a} |
| Δ71–80 | FlaB2 _{S2} missing ⁷¹ AIYITPNAGS ⁸⁰ |
| Δ81–90 | FlaB2 _{S2} missing ⁸¹ AAIDMNQVVL ⁹⁰ |
| Δ91–100 | FlaB2 _{S2} missing ⁹¹ TLSDGTTKT ¹⁰⁰ |
| Δ101–110 | FlaB2 _{S2} missing ¹⁰¹ TKYDTTAYTN ^{110 a} |
| Δ111–120 | FlaB2 _{S2} missing ¹¹¹ LTAGGDLYNT ^{120 a} |
| Δ121–130 | FlaB2 _{S2} missing ¹²¹ TTVNWSKLAD ^{130 a} |

(Continued)

Table 2. (Continued)

| Mutated FlaB2 derivatives | Description |
|----------------------------------|--|
| Δ131–140 | FlaB2 _{S2} missing ¹³¹ TTEFGIVEIQ ¹⁴⁰ |
| Δ141–150 | FlaB2 _{S2} missing ¹⁴¹ DADLSFTSSA ¹⁵⁰ |
| Δ151–160 | FlaB2 _{S2} missing ¹⁵¹ PVINKGDIVA ¹⁶⁰ |
| Δ161–170 | FlaB2 _{S2} missing ¹⁶¹ IIVSGVSFDT ¹⁷⁰ |
| Δ171–180 | FlaB2 _{S2} missing ¹⁷¹ RMEISGTVQP ¹⁸⁰ |
| Δ181–190 | FlaB2 _{S2} missing ¹⁸¹ EFGAPGVISF ¹⁹⁰ |
| Δ194–204 | FlaB2 _{S2} missing ¹⁹⁴ STFTEKV VSLQ ²⁰⁴ |
| Three-amino acid deletion | |
| Δ3AA | FlaB2 _{S2} missing ⁶¹ GTA ⁶³ |
| Substitution mutant | |
| SUB | FlaB2 _{S2} having ⁹¹ TLSDGTTKTV ¹⁰⁰ substituted with IIVSGVSFDT |

The mutant *flaB2_{S2}* genes were first generated in pCR2.1-TOPO and then cloned into the *M. maripaludis* expression vector pWLG40.

^a bold letters: N-glycosylation sequons with the asparagine underlined

doi:10.1371/journal.pone.0116402.t002

For construction of the mutant versions of *flaB2_{S2}* whose protein products would contain scanning deletions, inverse PCR and overlapping primers was employed, again with pKJ902 as template. The forward primer was designed to contain the *flaB2_{S2}* gene sequence flanking the desired in-frame 30 bp deletion. The reverse primer was complementary to the forward primer sequence upstream of the deletion (Table 2). After *DpnI* digestion, purified PCR products were transformed into *E. coli* TOP10 competent cells. Recombinant plasmids were extracted from the transformants and used as template for amplifying the *flaB2_{S2}* mutant genes by PCR with the complementation primers listed in Table 2. The smaller *flaB2_{S2}* mutant genes were identified by agarose gel electrophoresis of the PCR products which were also sequenced to confirm the deletion. The same protocol was used to generate the 3 amino acid deletion, ⁶¹GTA⁶³, where the deletion of the 9bp resulted in the removal of an *RsaI* restriction site. This allowed for the screening of the *flaB2_{S2}* gene in plasmids carried by transformants for the small deletion by digestion of subsequent *flaB2_{S2}* PCR products with *RsaI*. Lastly, a mutant *flaB2_{S2}* gene encoding a mutated FlaB2_{S2} protein with a 10-amino acid deletion at ⁹¹TLSDGTTKTV¹⁰⁰ had those amino acids replaced with a copy of the 10 amino acids at ¹⁶¹IIVSGVSFDT¹⁷⁰, thereby generating a substitution mutant version of FlaB2_{S2} (SUB) that was still the same length as the wildtype version. All the mutant versions of *flaB2_{S2}* generated were sequenced to confirm the mutations.

Construction of complementation vectors

To generate complementation plasmids for *M. maripaludis* S2, mutant *flaB2_{S2}* genes in the pCR2.1-TOPO vector were PCR amplified using complementation primers with an *NsiI* restriction site incorporated into the forward primer and an *XbaI* site into the reverse primer (Table 2). After *NsiI* and *XbaI* digestion, the PCR product was cloned into the shuttle vector pWLG40 where transcription of the cloned gene is under the control of the strong constitutive *hmv* promoter [48]. Mutant *flaB2_{S2}* genes in pWLG40 were sequenced to confirm the insert gene sequence. As a further control, plasmids were re-isolated from the complemented cells and re-sequenced.

Table 3. Primers used in this study^a.

| | Complementation primers | Notes |
|--|--|-------------|
| comp-F | CTAGATGCATGAAAATAACAGAATTCATGAAAAGCAAAAAAGGTGCTTC | <i>NsiI</i> |
| comp-R | ACGTTCTAGATTATTGTAATGAACTACTTTTCAGTGAATGTTGAAG | <i>XbaI</i> |
| SDM primers | | |
| Ten-amino acid deletion primers | | |
| 2-F | ATTCATGAAAAGCAAAAAAGGTGCTATTGCAATGGTATTAGTTGCTGCAG | |
| 2-R | AGCACCTTTTTTGCTTTTCATGAATTCTG | |
| 4-F | ATTCATGAAAAGCAAAAAAGGTGCTTCTGGAATTGCAATGGTATTAGTTGCTGCAG | |
| 4-R | TCCAGAAGCACCTTTTTTGCTTTTCATGAATTCTG | |
| 11-F | GGAATTGGTACCTTGATTGTTTTGCAAGCGTTTAAATTAACACAAGCG | |
| 11-R | AAAAACAATCAAGGTACCAATTCCAG | |
| 21-F | CAATGGTATTAGTTGCTGCAGTTGCATTACAACAAAAAGCTTCAACAACCTGG | |
| 21-R | TGCAACTGCAGCAACTAATACCATTGC | |
| 31-F | CGTTTAAATTAACACAAGCGGATTGATAGTACCGAACAGGTTGCAAGC | |
| 31-R | GAATCCGCTTGTGTTAATTAACGCTTGC | |
| 41-F | CAACAAAAAGCTTCAACAACCTGGTAAACAAATTATGGGTATTAGCGGATACC | |
| 41-R | TTTACCAGTTGTTGAAGCTTTTTGTTG | |
| 51-F | GTACCGAACAGGTTGCAAGCGGTTAGGTACTGCTAACGCAAACATTAC | |
| 51-R | TAAACCGCTTGCAACCTGTTCCG | |
| 61-F | GGGTATTAGCGGATACCAAGCAGCAATCTACATAACTCCTAACGCAGG | |
| 61-R | TGCTTGGTATCCGCTAATACCCATAATTTG | |
| 71-F | GCTAACGCAAAACATTACAAAATTAGCTGCAATAGACATGAATCAGGTTG | |
| 71-R | TAATTTTGTAATGTTTGCGTTAGC | |
| 81-F | CATAACTCCTAACGCAGGAAGTACACTTTCAGACGGAACCTACAAAACTG | |
| 81-R | ACTTCCTGCGTTAGGAGTTATGTAG | |
| 91-F | GCAATAGACATGAATCAGGTTGTTTAACTAAATACGATACTACCGCATACAC | |
| 91-R | TAAACAACCTGATTCATGTCTATTGC | |
| 101-F | CTTTCAGACGGAACCTACAAAACTGTTCTAACTGCAGGTGGAGACCTTTAC | |
| 101-R | AACAGTTTTGTAGTTCGGTCTGAAAG | |
| 111-F | ACGATACTACCGCATACACAAACACAACCTGTAACTGGTCAAAATTAGC | |
| 111-R | GTTTGTGTATGCGGTAGTATCGTATTTAG | |
| 121-F | GCAGGTGGAGACCTTTACAACACTACTACAGAATTTGGAATAGTTGAAATTC | |
| 121-R | AGTGTGTAAAGGTCTCCACCTGCAG | |
| 131-F | GTAAACTGGTCAAAATTAGCAGATGATGCAGATCTTTCATTTACAAG | |
| 131-R | ATCTGCTAATTTTGACCAGTTTACAG | |
| 141-F | GAATTTGGAATAGTTGAAATTCAACCAGTTATCAACAAAGGTGACATAG | |
| 141-R | TTGAATTTCAACTATTCCAAATTCTG | |
| 151-F | GATCTTTCATTACAAAGTTCAGCAATTATTGTAAGCGGAGTTTCATTGC | |
| 151-R | TGCTGAACCTTGTAATGAAAGATCTGC | |
| 161-F | CAACAAAGGTGACATAGTTGCAAGAATGGAAATTTAGGTACTGTTTCAG | |
| 161-R | TGCAACTATGTCACCTTTGTTGATAACTGG | |
| 171-F | GTAAGCGGAGTTTCATTTCGATACAGAATTTGGTGCTCCAGGAGTTATTTG | |
| 171-R | TGTATCGAATGAACTCCGCTTAC | |
| 181-F | GGAAATTTAGGTACTGTTTCAGCCAACACACCTTCAACATTCACTG | |
| 181-R | TGGCTGAACAGTACCTGAAATTTCC | |
| 194-F | CATTACCCACACCTTAAACATTCACTGAAAAAGTA | |
| 194-R | TACTTTTTCAGTGAATGTTAAGGTGTGGTGAATG | |

(Continued)

Table 3. (Continued)

| | Complementation primers | Notes |
|--|---|-------|
| Three-amino acid deletion primers | | |
| 3aa-F | <i>ATGGGTATTAGCGGATACCAAGCAAACGCAAACATTACAAAATTAGC</i> | |
| 3aa-R | <i>TGCTTGGTATCCGCTAATACCCATAATTTG</i> | |
| Ten-amino acid substitution (sub) primers | | |
| sub-F | <i>TGTAAGCGGAGTTTCATTGATACAACATAAATACGATACTACCGC</i> | |
| sub-R | <i>CGAATGAAACTCCGCTTACAATAATTAACAACCTGATTCATGTC</i> | |
| N-glycosylation site mutation primers | | |
| Q1-F | <i>GTACTGCTAACGCACAAATTACAAAATTAGC</i> | |
| Q1-R | <i>GCTAATTTTGTAATTTGTGCGTTAGCAGTAC</i> | |
| Q2-F | <i>CTACCGCATACACACAATAACTGCAGGTGGAG</i> | |
| Q2-R | <i>CTCCACCTGCAGTTAGTTGTGTGTATGCGGTAG</i> | |
| Q3-F | <i>GTGGAGACCTTTACAAACTACAACGTAAACTG</i> | |
| Q3-R | <i>CAGTTTACAGTTGTAGTTGGTAAAGGTCTCCAC</i> | |
| Q4-F | <i>AACACTACAACGTACAATGGTCAAAATTAGC</i> | |
| Q4-R | <i>GCTAATTTTGACCATTTGTACAGTTGTAGTGT</i> | |
| D1-F | <i>GTACTGCTAACGCAGACATTACAAAATTAGC</i> | |
| D1-R | <i>GCTAATTTTGTAATGTCTGCGTTAGCAGTAC</i> | |
| D2-F | <i>CTACCGCATACACAGACCTAACTGCAGGTGGAG</i> | |
| D2-R | <i>CTCCACCTGCAGTTAGGTCTGTGTATGCGGTAG</i> | |
| D3-F | <i>GTGGAGACCTTTACGACACTACAACGTAAACTG</i> | |
| D3-R | <i>CAGTTTACAGTTGTAGTGTGTAAGGTCTCCAC</i> | |
| D4-F | <i>AACACTACAACGTAGACTGGTCAAAATTAGC</i> | |
| D4-R | <i>GCTAATTTTGACCACTCTACAGTTGTAGTGT</i> | |

^aUnderlined: restriction enzyme sites

Italic bold: reverse complementary sequences in primer pairs

Italics: mutated amino acid codon

Underlined in italics: mutated DNA base

doi:10.1371/journal.pone.0116402.t003

Complementation of a $\Delta flaB2_{S2}$ mutant using mutant $flaB2_{S2}$ derivatives

To determine if the mutant FlaB_{2S2} proteins generated above could restore archaeallation and motility in the $\Delta flaB2_{S2}$ mutant, recombinant pWLG40 plasmids carrying the various mutant $flaB2_{S2}$ derivatives were transformed individually into the $\Delta flaB2_{S2}$ mutant using a PEG-based method [41,50]. Transformants were cultured in Balch medium III containing 0.25 µg/mL puromycin for plasmid selection [48].

Western blot analysis of the $\Delta flaB2_{S2}$ mutant complemented with mutant $flaB2_{S2}$ derivatives

Whole cell lysates of complemented cells carrying the various mutant $flaB2_{S2}$ genes were separated by SDS-PAGE (15% gels) and then transferred onto an Immobilon-P membrane (Millipore Inc.) [51]. Mutant FlaB_{2S2} proteins were detected using chicken anti-FlaB_{2S2} specific primary antibody [41]. Horseradish peroxidase-conjugated rabbit anti-chicken immunoglobulin Y (Jackson Immuno Research Laboratories) was used as secondary antibody, and the blots were developed using Immobilon Western Chemiluminescent HRP Substrate (Millipore Inc.).

Swarming assay of the $\Delta flaB2_{S2}$ mutant complemented with mutant $flaB2_{S2}$ derivatives

Complemented $\Delta flaB2_{S2}$ strains carrying plasmids with mutant $flaB2_{S2}$ genes encoding proteins having mutations at the various N-glycosylation sites were examined for motility using semi-solid swarm plates [22]. Briefly, the OD₆₀₀ of an overnight cell culture was measured and adjusted to 1.0. Five microliters of the adjusted cell culture were inoculated onto semi-solid Balch medium containing 0.25% (w/v) agar using a micropipette in an anaerobic chamber by stabbing the tip into the agar. Plates were incubated in an anaerobic canister at 37°C for 4 or 6 days.

Electron microscopy of the $\Delta flaB2_{S2}$ mutant complemented with mutant $flaB2_{S2}$ derivatives

Complemented *M. maripaludis* $\Delta flaB2_{S2}$ cells carrying mutant $flaB2_{S2}$ genes were collected from an overnight culture by centrifugation at 20 000 g for 1 min, washed with 2% (w/v) NaCl and resuspended in phosphate-buffered saline. Resuspended cells were loaded onto carbon-Formvar-coated copper grids and stained with 2% phosphotungstic acid, pH 7.0. Grids were examined in a Hitachi 7000 electron microscope operating at an accelerating voltage of 75 kV.

Results and Discussion

Generation of mutant $flaB2_{S2}$ derivatives

While deletions in genes that affect N-glycosylation are known to cause severe defects in archaeallation and motility [18,22,28,29], it is not clear if the defects are related directly to the inability of non-glycosylated archaeallins or archaeallins glycosylated with truncated glycans to assemble into archaeella, or whether the glycosylation defect affected other steps in the assembly of archaeella. For example, it may be that another protein critical for assembly of archaeella, but not an archaeallin, must be glycosylated in order to function properly. In *Hfx. volcanii* H53, changing the sequence of the major archaeallin *flgA* at any of the 3 examined sequons so that the encoded amino acid changed from Asn to Gln led to mutant forms of the protein that could not rescue the swimming defect of an *flgA* deletion strain, suggesting that each glycosylation site was necessary for archaeallation [18]. However, this is not the case for *M. maripaludis* S2. Previous work in this methanogen showed that a strain that had a spontaneous mutation in $flaB2_{S2}$ which led to the loss of the 2nd N-glycosylation site of the archaeallin that is normally decorated with the N-linked tetrasaccharide, was, nonetheless, still archaeallated and motile [43]. To examine the possible role that each N-glycosylation site, either alone or in combination with other sites, might have on archaeella formation and motility in *M. maripaludis* S2, various mutant $flaB2_{S2}$ genes whose products were lacking single to quadruple N-glycosylation sites either by Asn to Gln (N to Q) substitution, or Asn to Asp (N to D) substitution of the N-glycosylation sequon asparagine were generated and cloned into the complementation vector pWLG40 (Table 2). For these mutant constructs we used D or Q followed by a number to indicate that the change was N to D or N to Q with the number representing the site changed, i.e. Q1 indicates mutant FlaB2_{S2} with an N to Q substitution at the 1st N-glycosylation site.

In addition, two other mutant genes, designated G6 and G10 (Fig. 1), whose products contain extra N-glycosylation sequons were generated and cloned into pWLG40. The G6 sequence encodes the wildtype FlaB2_{ARC} protein (i.e. FlaB2_{ARC} from *M. maripaludis* Δ RC). FlaB2_{ARC} and FlaB2_{S2} share 95% identity, with the differences almost exclusively confined to several N-glycosylation sites (Fig. 1). Compared to FlaB2_{S2}, FlaB2_{ARC} shares 3 sites, plus it has 3 additional sequons, ⁶⁰NGS⁶², ¹⁰⁴NIS¹⁰⁶, ¹²⁹NDT¹³¹, but it is missing the 2nd N-glycosylation site ¹¹⁰NLT¹¹² in FlaB2_{S2}. The G10 protein has all the sites present in FlaB2_{S2} and FlaB2_{ARC}, with 3

additional sites created in the hypervariable region at sites requiring only minimal amino acid changes to generate a total of 10 possible sites (Fig. 1). G6 and G10 both have the $^{26}\text{NIS}^{28}$ sequon in the N-terminal conserved region that is not occupied with N-glycan in FlaB_{2S2}. After transformation of these recombinant plasmid pWLG40-*flaB2S2* mutants into a Δ *flaB2S2* mutant, the complemented strains were examined for expression of the mutant FlaB_{2S2} proteins, archaeella formation and cell motility.

Western blot analysis of the Δ *flaB2S2* strain complemented with *flaB2S2* derivatives containing mutations at N-glycosylation sites

Western blots were run to detect the expression and stability of the various mutant versions of FlaB_{2S2} in the complemented Δ *flaB2S2* mutant. As shown in Fig. 2, all mutant versions of FlaB_{2S2} except G10 were successfully expressed in the Δ *flaB2S2* mutant. All mutant FlaB_{2S2} proteins were expressed in similar amounts and all appeared stable as judged by the general lack of any cross-reacting smaller molecular mass bands which could be indicative of protein degradation. The amount of the G10 version of FlaB_{2S2} detected in western blots was very low and could be only observed when blots were overexposed (data not shown). We have found previously that cells carrying mutations in any gene that prevents assembly of archaeella (as in the Δ *flaB2S2* mutant) often stop transcribing the *fla* operon after several sub-cultures in the laboratory. This then makes the complementation of the original gene deletion back to an archaeellated state impossible [22]. For this reason, the presence of FlaE, whose gene is a downstream member of the *fla* operon, was also confirmed by western blot to ensure that the *fla* operon was still transcribed in the Δ *flaB2S2* mutant during the course of the complementation experiments (data not shown) [41].

In general, mutant FlaB_{2S2} proteins missing N-glycosylation sites all had a smaller apparent molecular mass than that of wildtype FlaB_{2S2} when examined by western blotting, with the

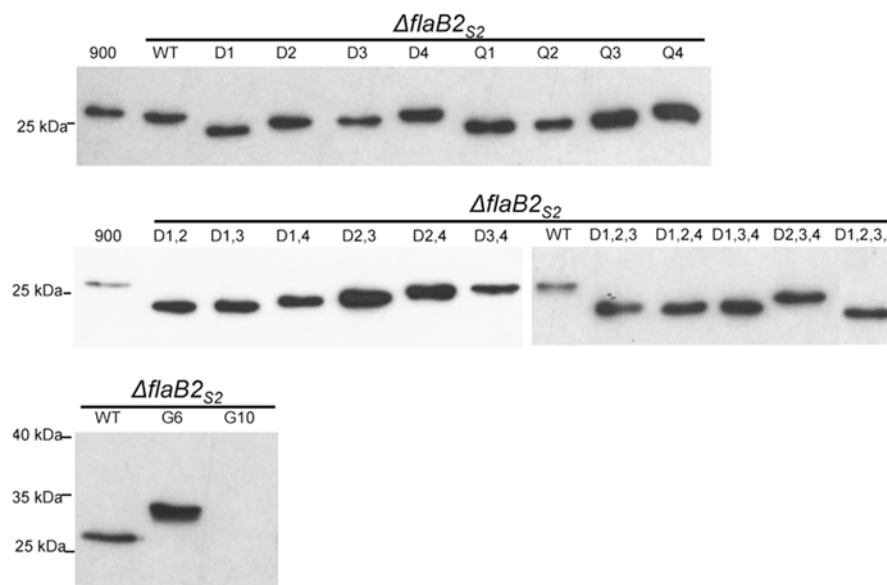


Fig 2. Western blot analysis of whole cell lysates of the Δ *flaB2S2* strain complemented with *flaB2S2* with mutations at various N-glycosylation sites. Mutant FlaB_{2S2} proteins missing single to quadruple N-glycosylation sites showed smaller apparent molecular mass than that of wildtype FlaB_{2S2}. The G6 which has extra glycosylation sequons migrated slower than wildtype FlaB_{2S2}. The expression of G10 was not detectable on this blot with normal exposure time. 900: wildtype *M. maripaludis* S2 Δ hpt. WT: Δ *flaB2S2* complemented with wildtype *flaB2S2*.

doi:10.1371/journal.pone.0116402.g002

possible exceptions of D4 and Q4 which ran at very close to wildtype size. The greater the number of *N*-glycosylation sites eliminated in a particular FlaB2_{S2} mutant, the faster the mutant proteins migrated, i.e., single-site mutants had the largest apparent molecular mass, and the quadruple-site mutant D1,2,3,4 had the smallest. However, the 8 single-site mutants did not migrate as proteins of the same apparent molecular mass. Of the 8 mutants, D1 and Q1, both of which had the 1st *N*-glycosylation site eliminated, had the smallest apparent molecular mass, while D4 and Q4 had the largest. Similar results were observed from the double-site and triple-site mutations. In the 6 double-site mutations, FlaB2_{S2} with D1,2 and D1,3 sites eliminated had the smallest apparent molecular mass, followed by FlaB2_{S2} with D1,4 and D2,3 sites eliminated, while the archaeallin having the D2,4 and D3,4 sites eliminated migrated with the largest apparent molecular mass. In the triple-site mutants, FlaB2_{S2} with any of the 1st *N*-glycosylation site eliminated (D1,2,3, D1,2,4 and D1,3,4) migrated at the same apparent molecular mass while FlaB2_{S2} with the other triple combination of sites eliminated (D2,3,4) migrated more slowly.

One possible explanation for the observed different electrophoretic mobilities is that mutant FlaB2_{S2} proteins lacking the same number of *N*-glycosylation sites have the same number of *N*-glycans attached but the attachment of *N*-glycan on some sequons might have effects on the local protein structure so that the glycoprotein is not able to be totally denatured by SDS, thus resulting in an unusual migration pattern. This unusual electrophoretic mobility has been observed in other similar studies and been the suggested explanation. Human erythropoietin (Epo) has 3 *N*-glycosylation sites, and the 3 single-site mutants generated by N to Q SDM showed uneven migrations on western blot, although all of the 3 mutants had the same theoretical molecular mass but differed only in the position of the *N*-glycans [52]. Similar uneven migration was also observed in the 4 single-site mutations of hepatitis C virus envelope protein E1 each missing one *N*-glycosylation site [53].

While local folding effects might explain the altered electrophoretic mobility, another possible explanation for this unusual western blot result is that elimination of the 1st *N*-glycosylation site might interfere with the cell's ability to *N*-glycosylate the remaining sites, resulting in FlaB2_{S2} where not all the remaining sequons are actually occupied (and so run as smaller molecular mass proteins). On the other hand, it may be that elimination of one or more glycosylation sites results in the attachment of glycan to the sequon ²⁶NTS²⁸ that is not glycosylated under our usual growth conditions. This could explain why, for example, the FlaB2_{S2} mutants that are missing the 4th *N*-glycosylation site (D4 and Q4) showed a larger apparent molecular mass than the other single mutants and close to wildtype size. If D4 and Q4, missing the 4th glycosylation site, now had *N*-glycan attached at the normally unused sequon, these mutant proteins would have an identical mass as the wildtype. There is precedent for glycosylation at one sequon influencing what happens at distant sites. For example, it has been reported for rabies virus glycoprotein that *N*-glycosylation at one sequon can influence processing of the *N*-glycans at a different site on the protein [54]. In *M. voltae* PS, the archaeella are composed of 4 archaeallins FlaA_{Mv}, FlaB1_{Mv}, FlaB2_{Mv} and FlaB3_{Mv}, which share high sequence similarity in the N-terminal conserved region with FlaB1_{S2} and FlaB2_{S2} [41,55]. Interestingly, the first 40 amino acids in the mature FlaB1_{Mv} and FlaB2_{Mv} including the ²⁶NTS²⁸ sequon, are identical to those of FlaB2_{S2}, but in the case of the *M. voltae* PS archaeallins, the ²⁶NTS²⁸ sequon was found to be occupied with *N*-linked glycan [12]. Clearly, this region of the archaeallin can be glycosylated and possibly the ²⁶NTS²⁸ sequon in FlaB2_{S2} might be able to be *N*-glycosylated in *M. maripaludis* S2 under different conditions.

The G6 mutant FlaB2_{S2} protein (identical to the FlaB2_{ΔRC}) with additional glycosylation sequons compared to wildtype FlaB2_{S2} had a larger apparent molecular mass (~32 kDa) than wildtype FlaB2_{S2} (~27 kDa) in western blots. Since G6 has 6 *N*-glycosylation sites (excluding the ²⁶NTS²⁸ sequon), its larger apparent molecular mass suggests that at least some, and

possibly all, of the extra sequons are, in fact, occupied since the mass of the tetrasaccharide is only 1036 Da [11]. Although the expression level of G10 was extremely low, on over-exposed western blots, the apparent molecular mass (37kDa) of this “artificially designed” glycoprotein was even larger than G6, indicating that AglB can recognize and transfer glycan to at least some of the newly introduced sequons in the hypervariable region.

Electron microscopy of the $\Delta flaB2_{S2}$ strain complemented with $flaB2_{S2}$ derivatives containing mutations at N-glycosylation sites

Complemented cells carrying FlaB_{2S2} proteins having mutations at N-glycosylation sites were examined by transmission electron microscopy for archaellation, and the results are listed in Table 4. The majority of the complementations either restored archaellation to essentially all cells or were unable to restore archaellation to any cells. In only a couple of cases did the complementation lead to a population which contained roughly equal number of archaellated and non-archaellated cells (D1,2 and D3,4). Fig. 3 shows electron microscopy pictures of a number of selected complements (Q2, Q4, D2, D3, D4, D1,3, D2,4, D1,2,4, D2,3,4, D1,2,3,4, G6 and G10).

The archaellation state of the 4 control strains was as expected. Wildtype Mm900 cells (900) were archaellated while the $\Delta flaB2_{S2}$ mutant strain was non-archaellated. Archaeella were

Table 4. Archaellation and swarming ability of complements bearing FlaB_{2S2} mutants at N-glycosylation sites.

| Complements | | Archaellation ^a | Motility |
|--------------------|----------|----------------------------|----------|
| Controls | WT | ++ (100%) | ++ |
| | Blank | - (0%) | - |
| NQ single | Q1 | - (3%) ^b | - |
| | Q2 | ++ (100%) | ++ |
| | Q3 | - (3%) ^b | - |
| ND single | Q4 | - (0%) | - |
| | D1 | - (3%) ^b | - |
| | D2 | ++ (100%) | ++ |
| ND double | D3 | - (0%) | - |
| | D4 | ++ (93%) | - |
| | D1,2 | + (47%) | + |
| | D1,3 | - (0%) | - |
| | D1,4 | ++ (97%) | ++ |
| | D2,3 | ++ (100%) | ++ |
| ND triple | D2,4 | ++ (100%) | + |
| | D3,4 | + (60%) | + |
| | D1,2,3 | - (0%) | - |
| | D1,2,4 | - (0%) | - |
| | D1,3,4 | - (0%) | - |
| | D2,3,4 | ++ (100%) | ++ |
| ND quadruple | D1,2,3,4 | - (0%) | - |
| Additional sequons | G6 | ++ (100%) | +++ |
| | G10 | - (0%) | - |

^aFor each strain a minimum of 30 random cells were assessed for the presence or absence of archaeella. Values in parentheses describe the percentage of cells with observable archaeella.

^bOnly a rare cell was observed with archaeella, typically very few in number and abnormally short.

doi:10.1371/journal.pone.0116402.t004

observed when the $\Delta flaB_{S2}$ strain was complemented with the wildtype version of $flaB_{S2}$, but not when the $\Delta flaB_{S2}$ strain was complemented with the empty vector pWL40.

In the 8 single-site mutation complements, 3 mutant versions of $FlaB_{S2}$ (Q2, D2 and D4), could restore archaeallation. In the 3 archaeallated complements, Q2 and D2 had different amino acid substitutions at the same 2nd N-glycosylation site. The N to D amino acid change at the 2nd sequon generated in this study replicates the spontaneous mutation in $flaB_{S2}$ that we previously reported [43]. Both that spontaneous mutant and the complemented cells carrying the mutant D2 gene generated in this study showed no impairment in archaeallation or swarming motility [43]. These results indicate that missing the 2nd N-glycosylation site alone does not significantly interfere with archaeallation. In contrast, complementation of the $\Delta flaB_{S2}$ strain with $flaB_{S2}$ lacking the 4th N-glycosylation site differed markedly depending on what amino acid the original Asn was changed to; cells complemented with the D4 version had archaeella under electron microscopy while cells complemented with the Q4 version did not (Fig. 3). None of the other single-site mutation complements (Q1, Q3, Q4, D1 and D3 (Fig. 3)) were considered archaeallated, although in each of the Q1, Q3 and D1 complementations a rare cell with short archaeella was observed (Table 4).

Among the 6 double-site mutation complements, all but the D1,3 version could assemble archaeella (electron micrographs of D1,3 and D2,4 complemented cells are shown in Fig. 3). This was surprising since many of these double-site mutants contained eliminated sites which if deleted alone resulted in non-archaellated cells. In the 4 triple-site mutation complements, 3 complements D1,2,3, D1,2,4 and D1,3,4 were non-archaellated, while archaeella could be assembled in D2,3,4 (Fig. 3). However, when all glycosylation sites were eliminated in the complementing version of $flaB_{S2}$ (D1,2,3,4), the $\Delta flaB_{S2}$ cells were not able to assemble archaeella. These results indicate that in *M. maripaludis* S2, archaeella can be assembled using $FlaB_{S2}$ lacking as many as 3 out of the 4 glycosylation sites, as long as the first site remained intact (D2,3,4) but not when the archaeallin is entirely non-glycosylated (D1,2,3,4).

In the two complementations where new sequons were introduced into $FlaB_{S2}$, different results were observed. In the G6 complemented cells, the $\Delta flaB_{S2}$ strain were now archaeallated, suggesting that the $FlaB_{S2}$ protein with extra N-glycan modifications in the hypervariable region could be incorporated into the archaeellar filament by the archaeella assembly apparatus in *M. maripaludis* S2. This was not unexpected since this version of $FlaB_2$ already exists naturally in the archaeallated *M. maripaludis* strain ΔRC . In contrast, no archaeella were observed on the $\Delta flaB_{S2}$ strain complemented with the G10 version. The G10 version had extra glycosylation sequons added to the internal hypervariable region of the protein. While this protein appeared to be modified at, at least, some of these additional sequons with glycan, judging from its higher apparent molecular mass in western blots, it was very poorly expressed in the cells under our normal growth conditions and this low expression may explain the lack of archaeella observed by electron microscopy (Fig. 3).

Swarming assays of complements with mutant $flaB_{S2}$ derivatives containing mutations at N-glycosylation sites

In addition to the restoration of archaeallation, the complemented cells were also examined for possible restoration of motility using semi-solid agar plates (Fig. 4A). Motility assay results are summarized in Table 4, which also incorporates the archaeallation status of the complemented strains for comparison.

In general, complemented cells in which archaeallation was restored were also motile on swarming plates and all of the complemented cells that were non-archaellated as determined by electron microscopy (D1, D3, Q1, Q3, D1,3, D1,2,3, D1,2,4, D1,3,4, D1,2,3,4 and G10) were

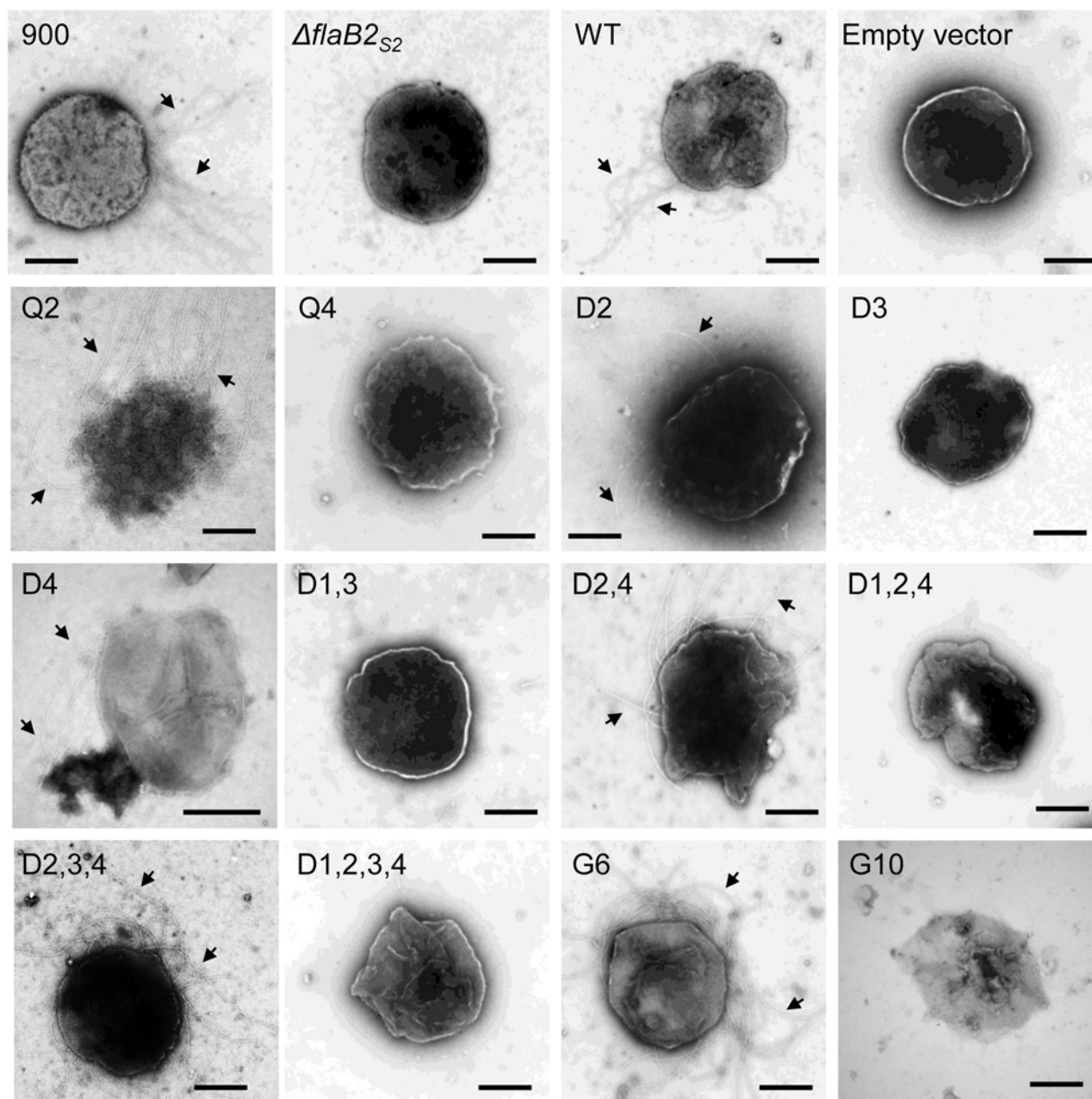


Fig 3. Transmission electron micrographs of select $\Delta flaB2_{S2}$ strain complemented with $flaB2_{S2}$ with mutations at various N-glycosylation sites. Wildtype Mm900 cell (900) was archaellated, while the $\Delta flaB2_{S2}$ mutant was not. Wildtype FlaB2_{S2} protein expressed in $\Delta flaB2_{S2}$ restored archaellation (WT), but the empty vector could not. Archaella were observed on surface of Q2, D2, D4, D2,4, D2,3,4 and G6 complemented cells. Cells complemented with Q4, D3, D1,3, D1,2,4, D1,2,3,4 and G10 were non-archaellated. Archaella are indicated by arrows. Bar equals 500 nm.

doi:10.1371/journal.pone.0116402.g003

also non-motile on swarm plates, even after an extra 2-day incubation (Fig. 4B). The unusual exception was the complementation with the D4 version of FlaB2_{S2} which was archaellated but non-motile (Fig. 3, Fig. 4A). However, among the motile complemented cells, the swarming diameter was not always returned to the wildtype level. Cells complemented with the $flaB2_{S2}$ genes carrying D2, Q2, D1,4, D2,3 and D2,3,4, mutations swarmed out to a similar distance on semi-solid agar (swarming diameter of D2/ WT = 1.01 ± 0.11 , Q2/WT = 1.10 ± 0.09 , D1,4/WT =

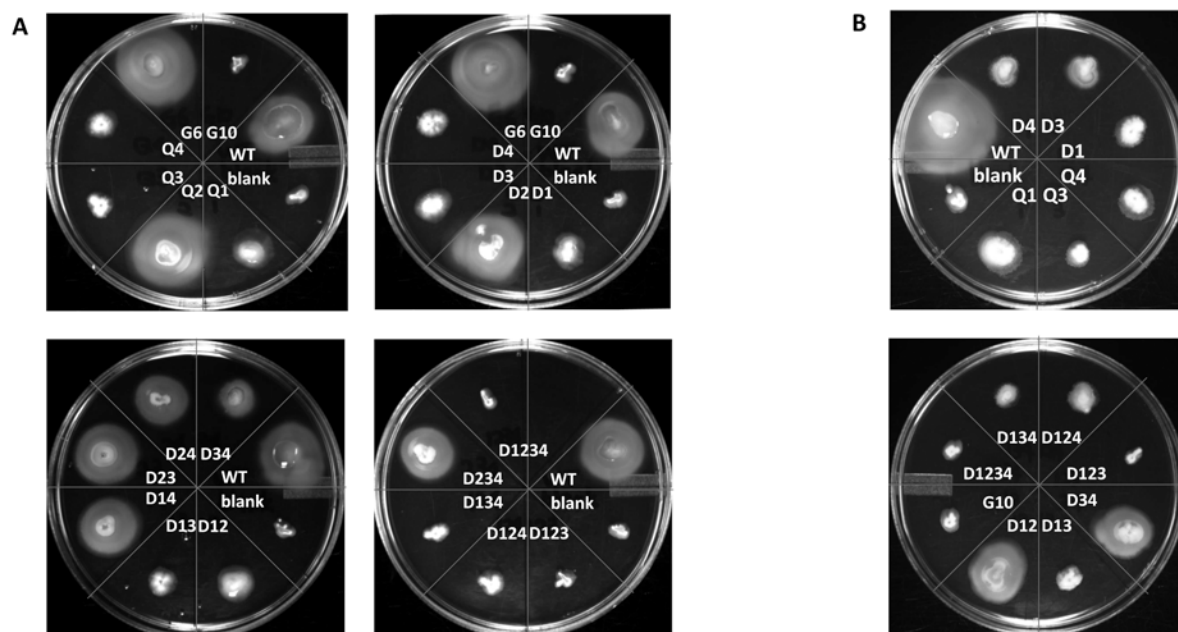


Fig 4. Swarming plates showing the motility of the $\Delta flaB2_{S2}$ strain complemented with $flaB2_{S2}$ with mutations at various N-glycosylation sites. A. Plates were incubated at 37°C for 4 days. **B.** Complemented cells that did not show motility or showed poor motility after 4 days incubation were incubated a further 2 days.

doi:10.1371/journal.pone.0116402.g004

0.93±0.14, D2,3/WT = 0.96±0.20, D2,3,4/WT = 1.08±0.22), while complements with the $flaB2_{S2}$ genes carrying D1,2, D2,4 and D3,4 had a smaller swarming diameter (swarming diameter of D1,2/WT = 0.51±0.05, D2,4/WT = 0.68±0.13, D3,4/WT = 0.52±0.07). For the D1,2 and D3,4 complementations, the smaller swarming distance may be explained by the lower percentage of cells that were observed by electron microscopy to be archaeellated, but in the case of the D2,4 all cells examined were archaeellated. Interestingly, G6 appeared hyper-motile as it consistently swarmed further than cells complemented with the wildtype version of $flaB2_{S2}$ (swarming diameter of G6/WT = 1.24±0.10).

In *Hfx. volcanii* H53, none of the 3 FlgA single-site mutation complements showed motility [18]. However, in this study, *M. maripaludis* S2 cells were still as motile as wildtype cells when the $\Delta flaB2_{S2}$ strains was complemented with $flaB2_{S2}$ with the D2,3,4 changes, in which archaeella were assembled using FlaB2_{S2} lacking 3 out of the 4 N-glycosylation sites. The structural protein (flagellin) of the functionally analogous bacterial swimming organelle, the flagellum, can also be modified with glycan, especially in Gram-negative bacteria, although the linkage is O-glycosidic rather than N-glycosidic [56,57]. The O-glycan modification in bacterial flagellin can be critical for flagella assembly, stabilization, motility, and even virulence in pathogens [56,58–60]. In *Pseudomonas syringae* pv. *tabaci*, flagellin FliC has 6 O-glycosylation sites, and single-site mutations in any of these sites resulted in various impairments in motility, while a mutant carrying mutations to eliminate all 6 O-glycosylation sites in FliC was non-motile [59]. The structural protein (pilin) from bacterial type-IV pili, structures which share several significant similarities with archaeella [10,34], can also be O-glycosylated [61,62]. Elimination of O-glycosylation of type IV pilin resulted in reduced twitching motility in *Pseudomonas aeruginosa* 1244 and *P. syringae* pv. *tabaci* but did not interfere with pili assembly [62,63]. However, in *P. aeruginosa* 5196 in which a different O-glycan was attached to the type IV pilin PilA, O-glycosylation played critical roles in both type IV pili assembly and twitching motility [2,64].

The results obtained with the G6 complemented cells indicate that an increase in glycosylation can lead to hyper-motility. The western blots results indicate that the G6 version of FlaB2 is hyper-glycosylated compared to the wildtype FlaB2_{S2} version. Of all the complemented strains, only the G6 complement consistently demonstrated an increased zone of swarming compared to the wildtype. Interestingly, similar results were also observed in regards the O-glycosylation of flagellin in *Helicobacter pylori* [65] where O-glycosylation of the flagellins FlaA and FlaB with pseudaminic acid is essential for flagella assembly and cell motility [66,67]. A *H. pylori* mutant defective in deglycosylation of flagellins showed both hyper-O-glycosylation (3 fold more pseudaminic acid) of FlaA as well as hyper-motility [65]. However, there is a limit to how many extra sequons can be added to archaeallins since archaeallin synthesis was very poor in the G10 complemented cells, even though the small amount of the G10 version detected was apparently modified at, at least, some of the extra sites.

The data obtained from the glycosylation site elimination mutants indicates that while no particular single site of glycosylation on FlaB2_{S2} is essential, nonetheless glycosylation at some site is necessary for archaeella formation. In the case of the 4 triple-site mutants it is clear that glycosylation of only site 1 is sufficient for archaeellation and motility. However, removal of the 1st site did not always lead to non-archaeellated cells as witnessed by the archaeellated and motile cells observed in the D1,4 complementation, suggesting that glycosylation of FlaB2_{S2} at several different combinations of sites could be sufficient for incorporation of the subunits into functional archaeella. In some ways, this is reminiscent of a situation in Wzc, a tyrosine autokinase essential for capsule formation in *E. coli*. Phosphorylation of tyrosine residues in the C-terminus of Wzc are necessary for its function but no single tyrosine is essential for phosphorylation and it was suggested that the overall level of phosphorylation rather than a precise combination of tyrosine residues accessible to phosphorylation is what is important for Wzc activity [68].

Western blot analysis of the $\Delta flaB2_{S2}$ strain complemented with *flaB2*_{S2} scanning deletions

To determine which regions of the FlaB2_{S2} protein are critical for archaeella formation, a series of FlaB2_{S2} scanning deletion mutants that sequentially lacked 10 amino acids were generated in the complementation vector pWLG40 and transformed into the $\Delta flaB2_{S2}$ mutant. The scanning deletions in *flaB2*_{S2} were identified since they migrated slightly faster than the wildtype version of *flaB2*_{S2} in 0.8% agarose gels due to the 30 bp deletion (Fig. 5 shows an example for screening of $\Delta 31-40$). For the first 10 amino acids, two versions were generated. The first was deleted for amino acids 2–10 (named as $\Delta 2-10$), leaving the +1 amino acid which we thought might be important for successful cleavage of the 12 amino acid signal peptide. We also generated a 4–10 amino acid deletion (named as $\Delta 4-10$) since the +3 glycine of the mature protein is needed for signal peptide removal in archaeallins of the related methanogen *M. voltae* PS [69].

Mutant FlaB2_{S2} proteins from whole cell lysates of the various complemented cells were detected using anti-FlaB2_{S2} specific antibody on western blot analysis, as shown in Fig. 6. In the 21 FlaB2_{S2} scanning deletions, 19 mutant proteins (all, except $\Delta 4-10$ and $\Delta 11-20$) were readily detected on western blot by anti-FlaB2_{S2} specific antibody, although the expression level of $\Delta 2-10$ and $\Delta 21-31$ was relatively lower compared to that of the other mutants. Evidence of some possible protein degradation was observed in the $\Delta 2-10$ and $\Delta 161-170$ FlaB2_{S2} as multiple lower molecular mass bands were detected in these two lanes. These results indicate that some of the mutant proteins were either not expressed or were unstable and degraded. Fourteen mutant proteins, including $\Delta 21-30$, $\Delta 31-40$, $\Delta 41-50$, $\Delta 51-60$, $\Delta 71-80$, $\Delta 81-90$, $\Delta 91-100$, $\Delta 131-140$, $\Delta 141-150$, $\Delta 151-160$, $\Delta 161-170$, $\Delta 171-180$, $\Delta 181-190$ and $\Delta 194-204$, had similar apparent molecular masses, which were smaller than FlaB2_{S2} from the wildtype strain Mm900 (900)

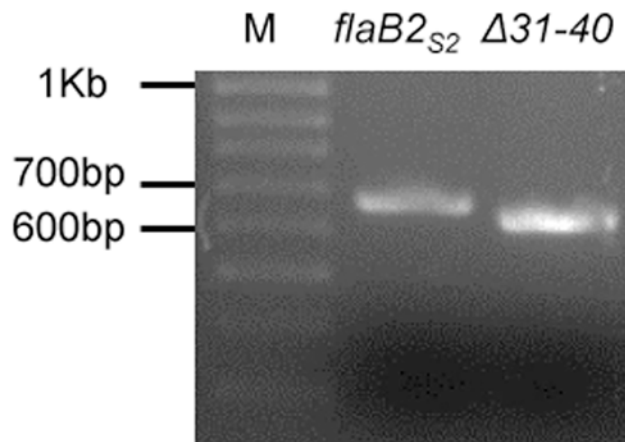


Fig 5. PCR screening of the $\Delta 31-40$ scanning deletion. Following the deletion procedure, the *flaB2_{S2}* gene was amplified using *flaB2_{S2}* complementation primers and the PCR product analyzed by agarose gel electrophoresis along with the amplification product obtained with the wildtype *flaB2_{S2}* gene using the same primers. The scanning deletion is readily distinguished from wildtype *flaB2_{S2}* by the faster migration of its 30 bp smaller PCR product M: 100 bp DNA ladder; *flaB2_{S2}*: PCR products using pKJ902 as template; $\Delta 31-40$: PCR products using plasmid isolated from one colony of the $\Delta 31-40$ transformants as template.

doi:10.1371/journal.pone.0116402.g005

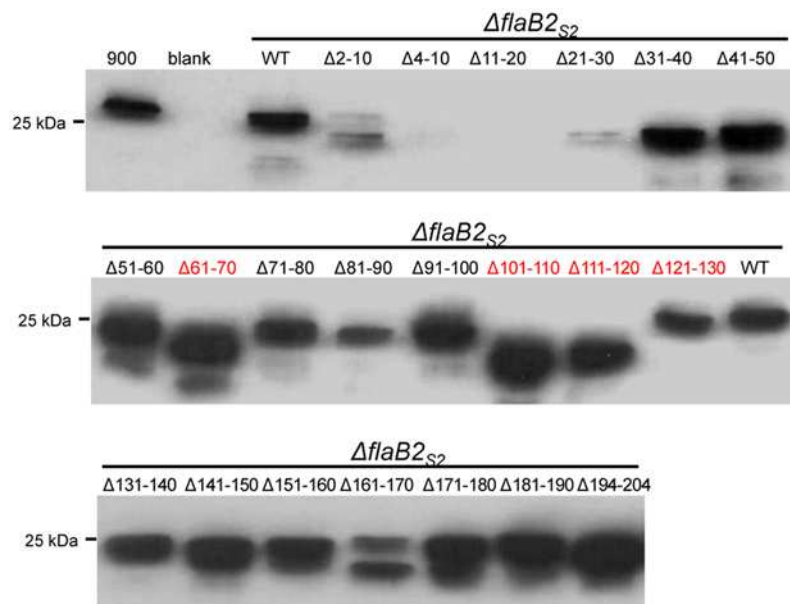


Fig 6. Western blot analysis of the $\Delta flaB2_{S2}$ strain complemented with *flaB2_{S2}* scanning deletions. Except for $\Delta 4-10$ and $\Delta 11-20$, all the *FlaB2_{S2}* scanning deletion proteins were expressed, although the expression level of $\Delta 2-10$ and $\Delta 21-30$ was relatively low. *FlaB2_{S2}* scanning deletion proteins $\Delta 61-70$, $\Delta 101-110$, $\Delta 111-120$ whose 10-amino acid deletion contains an N-glycosylation site (shown in red) had smaller apparent molecular masses due to the loss of N-glycan usually attached at this site. $\Delta 121-130$ missing the 4th N-glycosylation site (shown in red) had unusual bigger apparent molecular mass than the other 3 mutants also missing N-glycosylation site.

doi:10.1371/journal.pone.0116402.g006

or from the $\Delta flaB_{S2}$ strain complemented with the wildtype version of *flaB*_{S2}. This is consistent with the fact that all these mutation proteins are 10 amino acids shorter than wildtype FlaB_{S2}. The upper band in the mutant $\Delta 2-10$ lane appears slightly larger than the neighboring WT lane. This might be due to the lack of processing of the archaeallin signal peptide in this deletion since in *M. voltae* PS the +3 glycine position was essential for cleavage of the signal peptide by the pre-archaeallin peptidase FlaK and this is missing in the $\Delta 2-10$ version of FlaB_{S2} [69]. The presence of the signal peptide does not prevent the attachment of N-glycans [37] so this version of FlaB_{S2} would be expected to have a full complement of attached N-glycans as well as the extra amino acids of the signal peptide contributing to make it run slightly larger in the western blots than the processed wildtype version of FlaB_{S2}.

The FlaB_{S2} mutants $\Delta 61-70$, $\Delta 101-110$ and $\Delta 111-120$ had even smaller apparent molecular masses compared to the FlaB_{S2} carrying other scanning deletions. This can be attributed to the fact that these three deletions result in the loss of one N-glycosylation sequon. Surprisingly, the scanning deletion that contains the remaining, 4th, glycosylation sequon, namely $\Delta 121-131$, does not follow this pattern. In this lone case, FlaB_{S2} migration in western blots is slower than the other three deletion mutants missing N-glycosylation sites. This observation is consistent with the results of the N-glycosylation sequon mutation complementations. In the case of both single 4th sequon mutants (D4 and Q4), FlaB_{S2} had a larger apparent molecular mass than the other single-site mutations (Fig. 2), suggesting either that the lack of glycosylation at this site has unusual effects on the migration of FlaB_{S2} in western blots or that when the 4th glycosylation site is not available, the normally unoccupied ²⁶NTS²⁸ is now decorated with glycan, adding to the molecular mass. Further studies are necessary to confirm the glycosylation status of this ²⁶NTS²⁸ sequon in FlaB_{S2} in these mutant proteins.

Electron microscopy of the $\Delta flaB_{S2}$ strain complemented with FlaB_{S2} scanning deletions

To examine if $\Delta flaB_{S2}$ cells could assemble archaeella after being complemented with any of the FlaB_{S2} scanning deletions, cells from each complementation were observed by transmission electron microscopy for the presence of archaeella. All of the 21 10-amino acid scanning deletion complements were found to remain non-archaeallated (data not shown) even though most of them produced FlaB_{S2} detected by western blot. These results suggested that either all regions of the molecule were essential for archaeella formation or that a certain critical archaeallin length is important for the archaeella filament to be assembled.

Since none of the FlaB_{S2} scanning deletion mutants could restore archaeallation, we suspected that the 10-amino acid deletion in the scanning deletions was too long for FlaB_{S2} to be assembled into archaeella. To address this, we created a shorter 3-amino acid deletion in the hypervariable region of FlaB_{S2}. This protein was detected by western blot at a similar apparent molecular mass as the wildtype FlaB_{S2} (Fig. 7A). The examination of $\Delta flaB_{S2}$ cells complemented with the $\Delta 3AA$ version of *flaB* by electron microscopy revealed that even with this short deletion, only approximately half of the complemented cells were archaeallated (Fig. 7B). These results suggest that a 3-amino acid deletion might be the shortest deletion that FlaB_{S2} could tolerate and still be assembled into archaeella filaments.

We also tried to examine the possible length requirement of archaeallins in a different way. In a FlaB_{S2} that was already deleted for ⁹¹TLSDGTTKT¹⁰⁰, we inserted into this spot IIVSGVSFDT (originally from ¹⁶¹IIVSGVSFDT¹⁷⁰), creating a FlaB_{S2} hybrid that had amino acids 91–100 replaced with a second copy of amino acids 161–170 so that the resulting length of the FlaB_{S2} (dubbed a substitution; SUB) was wildtype. Both the donor and the acceptor regions are located in the hypervariable region of FlaB_{S2}, and do not contain N-glycosylation

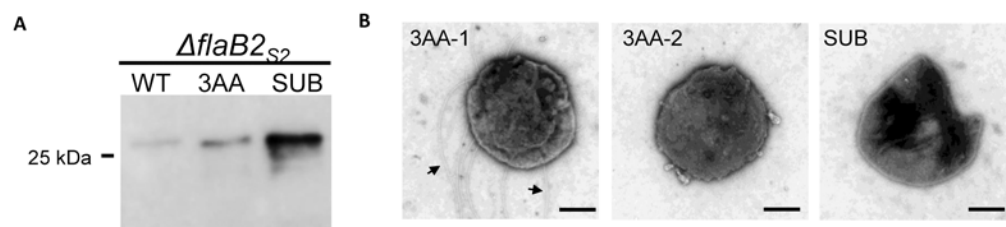


Fig 7. Analysis of the $\Delta flaB2_{S2}$ strain complemented with $flaB2_{S2}$ carrying the 3-amino acid deletion (3AA) or the substitution version of $flaB2_{S2}$ (SUB). A. Western blot analysis of the $\Delta flaB2_{S2}$ strain complemented with $flaB2_{S2}$ carrying the 3-amino acid deletion (3AA) or the substitution version of $flaB2_{S2}$ (SUB). 3AA and SUB had similar apparent molecular mass as wildtype FlaB2_{S2}. B. Transmission electron micrographs of the $\Delta flaB2_{S2}$ strain complemented with the 3AA or SUB versions of FlaB2_{S2}. In the case of the 3AA complemented cells, both archaeellated cell (3AA-1) and non-archaeellated cell (3AA-2) are shown. Arrows show the archaeella. Bar equals 500 nm.

doi:10.1371/journal.pone.0116402.g007

sequons to minimally reduce the effects from disruption of the conserved regions that might be involved in subunit-subunit interaction or in glycosylation. The SUB protein was expressed in the complement cells and showed similar apparent molecular mass as that of WT protein, as expected (Fig. 7A). However, the SUB protein complement could not restore archaeellation either (Fig. 7B), suggesting that the particular 10-amino acid sequence ⁹¹TLSDGTTKTV¹⁰⁰ is critical for archaeella assembly, despite the fact it is located in a hypervariable region of the molecule. We had anticipated that at least some of the scanning deletions covering the hypervariable region may have been tolerated and allow for formation of archaeellation while those located in the conserved N-terminus believed to critical for subunit-subunit interactions in the filament would not be tolerated [70,71]. It is known that in the case of bacterial flagellins large internal deletions can be accepted; for instance in *E. coli*, the 493 amino acid flagellin can be reduced by internal deletions so that only the N-terminal 193 residues and the 117 C-terminal amino acids are required for filament formation [72]. In addition, sequences in the internal hypervariable region of bacterial flagellin can be replaced with completely unrelated sequences [73]. This is also true for archaeallins in *Halobacterium salinarum* where both FLAG (8 amino acid peptide) and a gold-binding 12 amino acid peptide have been inserted into variable regions of different archaeallins and these mutant proteins were still able to be assembled into archaeella [74]. However, for type IV pilins, it has been shown in a number of studies that very small changes at key amino acids in the major pilins can result in instability of the pilins and ones that cannot assemble into pili [75–77].

Archaeella are unique swimming organelles that are thought to be assembled like bacterial type IV pili but function like bacterial flagella by filament rotation [10,33,34,78]. So far little is known about details of the incorporation of individual archaeallins into the archaeella filament. N-glycosylation seems to be a common modification of archaeallin, but the relationship between N-glycosylation and archaeella assembly is unclear [1,40]. In this study, we investigated the effects of eliminating potential N-glycosylation sites as well as scanning deletions of the archaeallin FlaB2_{S2} on archaeella assembly and function in *M. maripaludis* S2. In *M. maripaludis* S2, functional archaeella can be assembled using FlaB2_{S2} lacking as many as 3 out of 4 glycosylation sites (D2,3,4), but not when the archaeallin is entirely non-glycosylated (D1,2,3,4). A hyper-N-glycosylated version of FlaB2_{S2} (G6) resulted in hyper-motile *M. maripaludis* S2 cells. Attempts to define essential and nonessential domains of the archaeallin by scanning deletion analysis revealed that no contiguous 10 amino acid stretch could be deleted and still have the archaeallin complement a $\Delta flaB2_{S2}$ strain back to an archaeellated phenotype.

Author Contributions

Conceived and designed the experiments: YD SIA JPJC KFJ. Performed the experiments: YD KU SIA KM AB CK KFJ. Analyzed the data: YD KU SIA KM AB CK KFJ. Contributed reagents/materials/analysis tools: SIA CK JPJC KFJ. Wrote the paper: YD KFJ.

References

- Jarrell KF, Ding Y, Meyer BH, Albers SV, Kaminski L, et al. (2014) N-linked glycosylation in archaea: A structural, functional, and genetic analysis. *Microbiol Mol Biol Rev* 78: 304–341. doi: [10.1128/MMBR.00052-13](https://doi.org/10.1128/MMBR.00052-13) PMID: [24847024](https://pubmed.ncbi.nlm.nih.gov/24847024/)
- Nothaft H, Szymanski CM (2010) Protein glycosylation in bacteria: Sweeter than ever. *Nature Rev Microbiol* 8: 765–778. doi: [10.1038/nrmicro2383](https://doi.org/10.1038/nrmicro2383) PMID: [20948550](https://pubmed.ncbi.nlm.nih.gov/20948550/)
- Aebi M (2013) N-linked protein glycosylation in the ER. *Biochim Biophys Acta* 1833: 2430–2437. doi: [10.1016/j.bbamcr.2013.04.001](https://doi.org/10.1016/j.bbamcr.2013.04.001) PMID: [23583305](https://pubmed.ncbi.nlm.nih.gov/23583305/)
- Larkin A, Imperiali B (2011) The expanding horizons of asparagine-linked glycosylation. *Biochemistry* 50: 4411–4426. doi: [10.1021/bi200346n](https://doi.org/10.1021/bi200346n) PMID: [21506607](https://pubmed.ncbi.nlm.nih.gov/21506607/)
- Weerapana E, Imperiali B (2006) Asparagine-linked protein glycosylation: From eukaryotic to prokaryotic systems. *Glycobiology* 16: 91R–101R. PMID: [16510493](https://pubmed.ncbi.nlm.nih.gov/16510493/)
- Eichler J (2013) Extreme sweetness: Protein glycosylation in archaea. *Nature Rev Microbiol* 11: 151–156. doi: [10.1038/nrmicro2957](https://doi.org/10.1038/nrmicro2957) PMID: [23353769](https://pubmed.ncbi.nlm.nih.gov/23353769/)
- Burda P, Aebi M (1999) The dolichol pathway of N-linked glycosylation. *Biochim Biophys Acta* 1426: 239–257. PMID: [9878760](https://pubmed.ncbi.nlm.nih.gov/9878760/)
- Nothaft H, Scott NE, Vinogradov E, Liu X, Hu R, et al. (2012) Diversity in the protein N-glycosylation pathways within the *Campylobacter* genus. *MolCell Proteomics* 11: 1203–1219. doi: [10.1101/pdb.ip071761](https://doi.org/10.1101/pdb.ip071761) PMID: [23118356](https://pubmed.ncbi.nlm.nih.gov/23118356/)
- Kaminski L, Lurie-Weinberger MN, Allers T, Gophna U, Eichler J (2013) Phylogenetic- and genome-derived insight into the evolution of N-glycosylation in archaea. *Mol Phylogenet Evol* 68: 327–339. doi: [10.1016/j.ympev.2013.03.024](https://doi.org/10.1016/j.ympev.2013.03.024) PMID: [23567024](https://pubmed.ncbi.nlm.nih.gov/23567024/)
- Jarrell KF, Albers SV (2012) The archaeallum: An old motility structure with a new name. *Trends Microbiol* 20: 307–312. doi: [10.1016/j.tim.2012.04.007](https://doi.org/10.1016/j.tim.2012.04.007) PMID: [22613456](https://pubmed.ncbi.nlm.nih.gov/22613456/)
- Kelly J, Logan SM, Jarrell KF, Vandyke DJ, Vinogradov E (2009) A novel N-linked flagellar glycan from *Methanococcus maripaludis*. *Carbohydr Res* 344: 648–653. doi: [10.1016/j.carres.2009.01.006](https://doi.org/10.1016/j.carres.2009.01.006) PMID: [19203750](https://pubmed.ncbi.nlm.nih.gov/19203750/)
- Voisin S, Houliston RS, Kelly J, Brisson JR, Watson D, et al. (2005) Identification and characterization of the unique N-linked glycan common to the flagellins and S-layer glycoprotein of *Methanococcus voltae*. *J Biol Chem* 280: 16586–16593. PMID: [15723834](https://pubmed.ncbi.nlm.nih.gov/15723834/)
- Ng SYM, Wu J, Nair DB, Logan SM, Robotham A, et al. (2011) Genetic and mass spectrometry analysis of the unusual type IV-like pili of the archaeon *Methanococcus maripaludis*. *J Bacteriol* 193: 804–814. doi: [10.1128/JB.00822-10](https://doi.org/10.1128/JB.00822-10) PMID: [21075925](https://pubmed.ncbi.nlm.nih.gov/21075925/)
- Abu-Qam M, Eichler J (2006) Protein N-glycosylation in archaea: Defining *Haloferax volcanii* genes involved in S-layer glycoprotein glycosylation. *Mol Microbiol* 61: 511–525. PMID: [16762024](https://pubmed.ncbi.nlm.nih.gov/16762024/)
- Kaminski L, Naparstek S, Kandiba L, Cohen-Rosenzweig C, Arbiv A, et al. (2013) Add salt, add sugar: N-glycosylation in *Haloferax volcanii*. *Biochem Soc Trans* 41: 432–435. doi: [10.1042/BST20120142](https://doi.org/10.1042/BST20120142) PMID: [23356324](https://pubmed.ncbi.nlm.nih.gov/23356324/)
- Peyfoon E, Meyer B, Hitchen PG, Panico M, Morris HR, et al. (2010) The S-layer glycoprotein of the crenarchaeote *Sulfolobus acidocaldarius* is glycosylated at multiple sites with the chitobiose-linked N-glycans. *Archaea* doi: [10.1155/2010/754101](https://doi.org/10.1155/2010/754101) PMID: [20936123](https://pubmed.ncbi.nlm.nih.gov/20936123/)
- Wieland F, Paul G, Sumper M (1985) Halobacterial flagellins are sulfated glycoproteins. *J Biol Chem* 260: 15180–15185. PMID: [3934156](https://pubmed.ncbi.nlm.nih.gov/3934156/)
- Tripepi M, You J, Temel S, Önder Ö, Brisson D, et al. (2012) N-glycosylation of *Haloferax volcanii* flagellins requires known *agl* proteins and is essential for biosynthesis of stable flagella. *J Bacteriol* 194: 4876–4887. doi: [10.1128/JB.00731-12](https://doi.org/10.1128/JB.00731-12) PMID: [22730124](https://pubmed.ncbi.nlm.nih.gov/22730124/)
- Chaban B, Voisin S, Kelly J, Logan SM, Jarrell KF (2006) Identification of genes involved in the biosynthesis and attachment of *Methanococcus voltae* N-linked glycans: Insight into N-linked glycosylation pathways in archaea. *Mol Microbiol* 61: 259–268. PMID: [16824110](https://pubmed.ncbi.nlm.nih.gov/16824110/)

20. Leigh JA, Albers SV, Atomi H, Allers T (2011) Model organisms for genetics in the domain archaea: Methanogens, halophiles, Thermococcales and Sulfolobales. *FEMS Microbiol Rev* 35: 577–608. doi: [10.1111/j.1574-6976.2011.00265.x](https://doi.org/10.1111/j.1574-6976.2011.00265.x) PMID: [21265868](https://pubmed.ncbi.nlm.nih.gov/21265868/)
21. Meyer BH, Albers SV (2013) Hot and sweet: Protein glycosylation in crenarchaeota. *Biochem Soc Trans* 41: 384–392. doi: [10.1042/BST20120296](https://doi.org/10.1042/BST20120296) PMID: [23356316](https://pubmed.ncbi.nlm.nih.gov/23356316/)
22. Vandyke DJ, Wu J, Logan SM, Kelly JF, Mizuno S, et al. (2009) Identification of genes involved in the assembly and attachment of a novel flagellin N-linked tetrasaccharide important for motility in the archaeon *Methanococcus maripaludis*. *Mol Microbiol* 72: 633–644. doi: [10.1111/j.1365-2958.2009.06671.x](https://doi.org/10.1111/j.1365-2958.2009.06671.x) PMID: [19400781](https://pubmed.ncbi.nlm.nih.gov/19400781/)
23. Meyer BH, Albers SV (2014) AglB, catalyzing the oligosaccharyl transferase step of the archaeal N-glycosylation process, is essential in the thermoacidophilic crenarchaeon *Sulfolobus acidocaldarius*. *Microbiology Open* 3: 531–543. doi: [10.1002/mbo3.185](https://doi.org/10.1002/mbo3.185) PMID: [24916761](https://pubmed.ncbi.nlm.nih.gov/24916761/)
24. Abu-Qarn M, Yurist-Doutsch S, Giordano A, Trauner A, Morris HR, et al. (2007) *Haloferax volcanii* AglB and AglD are involved in N-glycosylation of the S-layer glycoprotein and proper assembly of the surface layer. *J Mol Biol* 374: 1224–1236. PMID: [17996897](https://pubmed.ncbi.nlm.nih.gov/17996897/)
25. Kaminski L, Abu-Qarn M, Guan Z, Naparstek S, Ventura VV, et al. (2010) AglJ adds the first sugar of the N-linked pentasaccharide decorating the *Haloferax volcanii* S-layer glycoprotein. *J Bacteriol* 192: 5572–5579. doi: [10.1128/JB.00705-10](https://doi.org/10.1128/JB.00705-10) PMID: [20802039](https://pubmed.ncbi.nlm.nih.gov/20802039/)
26. Yurist-Doutsch S, Abu-Qarn M, Battaglia F, Morris HR, Hitchen PG, et al. (2008) AglF, aglG and aglI, novel members of a gene island involved in the N-glycosylation of the *Haloferax volcanii* S-layer glycoprotein. *Mol Microbiol* 69: 1234–1245. doi: [10.1111/j.1365-2958.2008.06352.x](https://doi.org/10.1111/j.1365-2958.2008.06352.x) PMID: [18631242](https://pubmed.ncbi.nlm.nih.gov/18631242/)
27. Yurist-Doutsch S, Magidovich H, Ventura VV, Hitchen PG, Dell A, et al. (2010) N-glycosylation in archaea: On the coordinated actions of *Haloferax volcanii* AglF and AglM. *Mol Microbiol* 75: 1047–1058. doi: [10.1111/j.1365-2958.2009.07045.x](https://doi.org/10.1111/j.1365-2958.2009.07045.x) PMID: [20487296](https://pubmed.ncbi.nlm.nih.gov/20487296/)
28. Meyer BH, Peyfoon E, Dietrich C, Hitchen P, Dell A, et al. (2013) Agl16, a thermophilic glycosyltransferase, mediating the last step of the N-glycan biosynthesis in the thermoacidophilic crenarchaeon *Sulfolobus acidocaldarius*. *J Bacteriol* 195: 2177–2186. doi: [10.1128/JB.00035-13](https://doi.org/10.1128/JB.00035-13) PMID: [23475978](https://pubmed.ncbi.nlm.nih.gov/23475978/)
29. Meyer BH, Zolghadr B, Peyfoon E, Pabst M, Panico M, et al. (2011) Sulfoquinovose synthase—an important enzyme in the N-glycosylation pathway of *Sulfolobus acidocaldarius*. *Mol Microbiol* 82: 1150–1163. doi: [10.1111/j.1365-2958.2011.07875.x](https://doi.org/10.1111/j.1365-2958.2011.07875.x) PMID: [22059775](https://pubmed.ncbi.nlm.nih.gov/22059775/)
30. Guan Z, Naparstek S, Calo D, Eichler J (2012) Protein glycosylation as an adaptive response in archaea: Growth at different salt concentrations leads to alterations in *Haloferax volcanii* S-layer glycoprotein N-glycosylation. *Environ Microbiol* 14: 743–753. doi: [10.1111/j.1462-2920.2011.02625.x](https://doi.org/10.1111/j.1462-2920.2011.02625.x) PMID: [22029420](https://pubmed.ncbi.nlm.nih.gov/22029420/)
31. Jarrell KF, Ding Y, Nair DB, Siu S (2013) Surface appendages of archaea: Structure, function, genetics and assembly. *Life* 3: 86–117. doi: [10.3390/life3010086](https://doi.org/10.3390/life3010086) PMID: [25371333](https://pubmed.ncbi.nlm.nih.gov/25371333/)
32. Lassak K, Ghosh A, Albers SV (2012) Diversity, assembly and regulation of archaeal type IV pili-like and non-type-IV pili-like surface structures. *Res Microbiol* 163: 630–644. doi: [10.1016/j.resmic.2012.10.024](https://doi.org/10.1016/j.resmic.2012.10.024) PMID: [23146836](https://pubmed.ncbi.nlm.nih.gov/23146836/)
33. Shahapure R, Driessen RP, Haurat MF, Albers SV, Dame RT (2014) The archaeallum: A rotating type IV pilus. *Mol Microbiol* 91: 716–723. doi: [10.1111/mmi.12486](https://doi.org/10.1111/mmi.12486) PMID: [24330313](https://pubmed.ncbi.nlm.nih.gov/24330313/)
34. Pohlschroder M, Ghosh A, Tripepi M, Albers SV (2011) Archaeal type IV pilus-like structures—evolutionarily conserved prokaryotic surface organelles. *Curr Opin Microbiol* 14: 1–7. doi: [10.1016/j.mib.2011.01.001](https://doi.org/10.1016/j.mib.2011.01.001) PMID: [21239215](https://pubmed.ncbi.nlm.nih.gov/21239215/)
35. Jarrell KF, VanDyke DJ, Wu J (2009) Archaeal flagella and pili. In: Jarrell KF, editor. *Pili and Flagella: Current Research and Future Trends*. Norfolk, U.K.: Caister Academic Press. pp. 215–234.
36. Bardy SL, Jarrell KF (2002) FlaK of the archaeon *Methanococcus maripaludis* possesses preflagellin peptidase activity. *FEMS Microbiol Lett* 208: 53–59. PMID: [11934494](https://pubmed.ncbi.nlm.nih.gov/11934494/)
37. Bardy SL, Jarrell KF (2003) Cleavage of preflagellins by an aspartic acid signal peptidase is essential for flagellation in the archaeon *Methanococcus voltae*. *Mol Microbiol* 50: 1339–1347. PMID: [14622420](https://pubmed.ncbi.nlm.nih.gov/14622420/)
38. Albers SV, Szabo Z, Driessen AJM (2003) Archaeal homolog of bacterial type IV prepilin signal peptidases with broad substrate specificity. *J Bacteriol* 185: 3918–3925. PMID: [12813086](https://pubmed.ncbi.nlm.nih.gov/12813086/)
39. Tripepi M, Imam S, Pohlschroder M (2010) *Haloferax volcanii* flagella are required for motility but are not involved in PibD-dependent surface adhesion. *J Bacteriol* 192: 3093–3102. doi: [10.1128/JB.00133-10](https://doi.org/10.1128/JB.00133-10) PMID: [20363933](https://pubmed.ncbi.nlm.nih.gov/20363933/)
40. Jarrell KF, Jones GM, Kandiba L, Nair DB, Eichler J (2010) S-layer glycoproteins and flagellins: Reporters of archaeal posttranslational modifications. *Archaea* doi: [10.1155/2010/612948](https://doi.org/10.1155/2010/612948)

41. Chaban B, Ng SY, Kanbe M, Saltzman I, Nimmo G, et al. (2007) Systematic deletion analyses of the *fla* genes in the flagella operon identify several genes essential for proper assembly and function of flagella in the archaeon, *Methanococcus maripaludis*. *Mol Microbiol* 66: 596–609. PMID: [17887963](#)
42. Ding Y, Jones GM, Uchida K, Aizawa SI, Robotham A, et al. (2013) Identification of genes involved in the biosynthesis of the third and fourth sugars of the *Methanococcus maripaludis* archaeallin N-linked tetrasaccharide. *J Bacteriol* 195: 4094–4104. doi: [10.1128/JB.00668-13](#) PMID: [23836872](#)
43. Jones GM, Wu J, Ding Y, Uchida K, Aizawa S, et al. (2012) Identification of genes involved in the acetamidino group modification of the flagellin N-linked glycan of *Methanococcus maripaludis*. *J Bacteriol* 194: 2693–2702. doi: [10.1128/JB.06686-11](#) PMID: [22408155](#)
44. Moore BC, Leigh JA (2005) Markerless mutagenesis in *Methanococcus maripaludis* demonstrates roles for alanine dehydrogenase, alanine racemase, and alanine permease. *J Bacteriol* 187: 972–979. PMID: [15659675](#)
45. Keswani J, Orkand S, Premachandran U, Mandelco L, Franklin MJ, et al. (1996) Phylogeny and taxonomy of mesophilic *methanococcus* spp. and comparison of rRNA, DNA hybridization, and phenotypic methods. *Int J Syst Bacteriol* 46: 727–735. PMID: [8782682](#)
46. Corder RE, Hook LA, Larkin JM, Frea JI (1983) Isolation and characterization of two new methane-producing cocci: *Methanogenium olentangi*, sp. nov., and *Methanococcus deltae*, sp. nov. *Arch Microbiol* 134: 28–32.
47. Balch WE, Fox GE, Magrum LJ, Woese CR, Wolfe RS (1979) Methanogens: Reevaluation of a unique biological group. *Microbiol Rev* 43: 260–296. PMID: [390357](#)
48. Gardner WL, Whitman WB (1999) Expression vectors for *Methanococcus maripaludis*: Overexpression of acetohydroxyacid synthase and beta-galactosidase. *Genetics* 152: 1439–1447. PMID: [10430574](#)
49. Papworth C, Bauer JC, Braman J, Wright DA (1996) Site-directed mutagenesis in one day with >80% efficiency. *Strategies* 9: 3–4. PMID: [8740480](#)
50. Tumbula DL, Makula RA, Whitman WB (1994) Transformation of *Methanococcus maripaludis* and identification of a *pstI*-like restriction system. *FEMS Microbiol Lett* 121: 309–314.
51. Towbin H, Staehelin T, Gordon J (1979) Electrophoretic transfer of proteins from polyacrylamide gels to nitrocellulose sheets: Procedure and some applications. *Proc Natl Acad Sci U S A* 76: 4350–4354. PMID: [388439](#)
52. Yamaguchi K, Akai K, Kawanishi G, Ueda M, Masuda S, et al. (1991) Effects of site-directed removal of N-glycosylation sites in human erythropoietin on its production and biological properties. *J Biol Chem* 266: 20434–20439. PMID: [1657925](#)
53. Dubuisson J, Duvet S, Meunier JC, Op De Beeck A, Cacan R, et al. (2000) Glycosylation of the hepatitis C virus envelope protein E1 is dependent on the presence of a downstream sequence on the viral polyprotein. *J Biol Chem* 275: 30605–30609. PMID: [10882734](#)
54. Wojczyk BS, Takahashi N, Levy MT, Andrews DW, Abrams WR, et al. (2005) N-glycosylation at one rabies virus glycoprotein sequon influences N-glycan processing at a distant sequon on the same molecule. *Glycobiology* 15: 655–666. PMID: [15677380](#)
55. Kalmokoff ML, Jarrell KF (1991) Cloning and sequencing of a multigene family encoding the flagellins of *Methanococcus voltae*. *J Bacteriol* 173: 7113–7125. PMID: [1718944](#)
56. Logan SM (2006) Flagellar glycosylation—a new component of the motility repertoire? *Microbiology* 152: 1249–1262. PMID: [16622043](#)
57. Merino S, Tomás JM (2014) Gram-negative flagella glycosylation. *Int J Mol Sci* 15: 2840–2857. doi: [10.3390/ijms15022840](#) PMID: [24557579](#)
58. Taguchi F, Shibata S, Suzuki T, Ogawa Y, Aizawa S, et al. (2008) Effects of glycosylation on swimming ability and flagellar polymorphic transformation in *Pseudomonas syringae* pv. *tabaci* 6605. *J Bacteriol* 190: 764–768. PMID: [18024523](#)
59. Taguchi F, Takeuchi K, Katoh E, Murata K, Suzuki T, et al. (2006) Identification of glycosylation genes and glycosylated amino acids of flagellin in *Pseudomonas syringae* pv. *tabaci*. *Cell Microbiol* 8: 923–938. PMID: [16681835](#)
60. Ewing CP, Andreishcheva E, Guerry P (2009) Functional characterization of flagellin glycosylation in *Campylobacter jejuni* 81–176. *J Bacteriol* 191: 7086–7093. doi: [10.1128/JB.00378-09](#) PMID: [19749047](#)
61. Castric P (1995) *pilO*, a gene required for glycosylation of *Pseudomonas aeruginosa* 1244 pilin. *Microbiology* 141: 1247–1254. PMID: [7773418](#)
62. Nguyen LC, Taguchi F, Tran QM, Naito K, Yamamoto M, et al. (2012) Type IV pilin is glycosylated in *Pseudomonas syringae* pv. *tabaci* 6605 and is required for surface motility and virulence. *Mol Plant Pathol* 13: 764–774. doi: [10.1111/j.1364-3703.2012.00789.x](#) PMID: [22353307](#)

63. Smedley JG 3rd, Jewell E, Roguskie J, Horzempa J, Syboldt A, et al. (2005) Influence of pilin glycosylation on *Pseudomonas aeruginosa* 1244 pilus function. *Infect Immun* 73: 7922–7931. PMID: [16299283](#)
64. Harvey H, Kus JV, Tessier L, Kelly J, Burrows LL (2011) *Pseudomonas aeruginosa* D-arabinofuranose biosynthetic pathway and its role in type IV pilus assembly. *J Biol Chem* 286: 28128–28137. doi: [10.1074/jbc.M111.255794](#) PMID: [21676874](#)
65. Asakura H, Churin Y, Bauer B, Boettcher JP, Bartfeld S, et al. (2010) *Helicobacter pylori* HP0518 affects flagellin glycosylation to alter bacterial motility. *Mol Microbiol* 78: 1130–1144. doi: [10.1111/j.1365-2958.2010.07393.x](#) PMID: [21091500](#)
66. Josenhans C, Vossebein L, Friedrich S, Suerbaum S (2002) The *neuA/flmD* gene cluster of *Helicobacter pylori* is involved in flagellar biosynthesis and flagellin glycosylation. *FEMS Microbiol Lett* 210: 165–172. PMID: [12044670](#)
67. Schirm M, Soo EC, Aubry AJ, Austin J, Thibault P, et al. (2003) Structural, genetic and functional characterization of the flagellin glycosylation process in *Helicobacter pylori*. *Mol Microbiol* 48: 1579–1592. PMID: [12791140](#)
68. Paiment A, Hocking J, Whitfield C (2002) Impact of phosphorylation of specific residues in the tyrosine autokinase, wzc, on its activity in assembly of group 1 capsules in *Escherichia coli*. *J Bacteriol* 184: 6437–6447. PMID: [12426330](#)
69. Thomas NA, Chao ED, Jarrell KF (2001) Identification of amino acids in the leader peptide of *Methanococcus voltae* preflagellin that are important in posttranslational processing. *Arch Microbiol* 175: 263–269. PMID: [11382222](#)
70. Trachtenberg S, Galkin VE, Egelman EH (2005) Refining the structure of the *Halobacterium salinarum* flagellar filament using the iterative helical real space reconstruction method: Insights into polymorphism. *J Mol Biol* 346: 665–676. PMID: [15713454](#)
71. Cohen-Krausz S, Trachtenberg S (2002) The structure of the archaeobacterial flagellar filament of the extreme halophile *Halobacterium salinarum* R1M1 and its relation to eubacterial flagellar filaments and type IV pili. *J Mol Biol* 321: 383–395. PMID: [12162953](#)
72. Kuwajima G (1988) Construction of a minimum-size functional flagellin of *Escherichia coli*. *J Bacteriol* 170: 3305–3309. PMID: [3290204](#)
73. Stocker BA, Newton SM (1994) Immune responses to epitopes inserted in *Ssalmonella* flagellin. *Int Rev Immunol* 11: 167–178. PMID: [7519231](#)
74. Beznosov SN, Pyatibratov MG, Veluri PS, Mitra S, Fedorov OV (2013) A way to identify archaeallins in *Halobacterium salinarum* archaeella by FLAG-tagging. *Cent Eur J Biol* 8: 828–834.
75. Giltner CL, Nguyen Y, Burrows LL (2012) Type IV pilin proteins: Versatile molecular modules. *Microbiol Mol Biol Rev* 76: 740–772. doi: [10.1128/MMBR.00035-12](#) PMID: [23204365](#)
76. Yang Z, Hu W, Chen K, Wang J, Lux R, et al. (2011) Alanine 32 in PilA is important for PilA stability and type IV pili function in *Myxococcus xanthus*. *Microbiology* 157: 1920–1928. doi: [10.1099/mic.0.049684-0](#) PMID: [21493683](#)
77. Kirn TJ, Lafferty MJ, Sandoe CM, Taylor RK (2000) Delineation of pilin domains required for bacterial association into microcolonies and intestinal colonization by *Vibrio cholerae*. *Mol Microbiol* 35: 896–910. PMID: [10692166](#)
78. Ghosh A, Albers SV (2011) Assembly and function of the archaeal flagellum. *Biochem Soc Trans* 39: 64–69. doi: [10.1042/BST0390064](#) PMID: [21265748](#)